Igneous Intrusions in the Faroe Shetland Basin and their Implications for Hydrocarbon Exploration; New Insights from Well and Seismic Data

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2

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ABSTRACT

Igneous sills and dykes that intrude pervasively into prospective sedimentary basins are a common occurrence in volcanic rifted margins, impacting the petroleum system and causing geological and technical drilling challenges during hydrocarbon exploration. The Faroe-Shetland Basin (FSB), NE Atlantic Margin, has been the focus of exploration for over 45 years, with many wells penetrating igneous intrusions. Utilising 29 FSB wells with 251 intrusions and 3D seismic data, this study presents new insights into the impacts that igneous intrusions have on hydrocarbon exploration. Examination of cores reveals that there can be up to 35% additional igneous rock in individual wells compared to estimates using seismic or petrophysical data alone, leading to potential underestimation of the igneous component in a basin. Furthermore, analysis of petrophysical data shows that within the FSB there are evolved intrusions such as diorite and rhyolite in addition to the commonly encountered basaltic intrusions. These evolved intrusions are difficult to recognise in seismic and petrophysical data and have historically been misidentified on seismic as exploration targets. Drilling data acquired through intrusions provide valuable insight into the problems exploration wells can encounter, often unexpectedly, many of which can be detrimental to safe drilling practice and result in prolonged non-productive time.

Keywords: *igneous intrusions, seismic imaging, drilling, Atlantic Margin*

INTRODUCTION

Igneous intrusions within petroliferous sedimentary basins have been the focus of recent research due to the importance of understanding how intrusions affect hydrocarbon exploration and the impact they have on the petroleum system such as reduced reservoir quality and source rock maturation (Holford *et al.,* 2013; Muirhead *et at.,* 2017, Rateau *et al.,* 2013; Schofield *et al.,* 2015; Senger *et al.,* 2017). Analysis of exploration wells and 3D seismic data acquired by the petroleum industry has resulted in a greater understanding of igneous intrusions in the subsurface (Smallwood & Maresh, 2002; Thomson and Hutton, 2004; Planke *et al.,* 2005; Hansen and Cartwright, 2006; Schofield et al. 2012a; Schofield *et al.,* 2015). Specifically, 3D seismic data has resulted in a better understanding of the morphologies, emplacement mechanisms and interconnectivity of intrusions in rifted margin sedimentary basins (Gibb & Kanaris-Sotiriou, 1988; Bell & Butcher, 2002; Thomson & Schofield, 2008; Schofield et al. 2015). Although previous work addresses the scientific applications such as intrusion morphologies and emplacement mechanisms, the significance of the research in relation to hydrocarbon exploration is often overlooked. Seismic data has provided valuable insights into magma plumbing systems, though such data typically only resolve intrusions 40 m in thickness and thus the role of thinner/smaller intrusions is less well understood. Furthermore, most 3D seismic data is acquired in sedimentary basins where magmatism is predominantly basaltic. Hence there is less knowledge about the seismic expression of evolved intrusions such as rhyolitic or dioritic compositions. Proper characterisation of the variable intrusion compositions and the prediction of the amount of missed igneous material in the subsurface is essential, as failure to understand this can result in important drilling implications, including poor hole condition, low rates of penetration and non-productive time.

This study addresses the implications igneous intrusions have for hydrocarbon exploration in the FSB and Atlantic Margin, expanding on recent work by Schofield *et al*, (2015). Notably, we detail the importance of understanding how drilling operations can be affected by igneous intrusions within the subsurface. Specifically, this paper will address three main elements. Firstly, how data bias and resolution limits result in fewer intrusions being identified. Secondly, how identification of evolved/felsic igneous rocks within the subsurface present a challenge for seismic imaging and petrophysical characterisation. Finally, the drilling complications resulting from penetrating intrusions highlights how they directly impact drilling operations, potentially incurring safety and environmental risks in addition to costly downtime. It should be noted that as the offshore exploration and drilling industry utilises substantial forms of terminology and abbreviations, we have included a table to allow for appropriate terminology descriptions and clarity (Table 3, supplementary material).

Despite the analysis focusing on the FSB, the themes and ideas explored in this paper are applicable to igneous hosted sedimentary basins worldwide and may help mitigate the risk of similar issues presented in this study occurring during future exploration.

GEOLOGICAL HISTORY

The Faroe-Shetland Basin (FSB) is located between the Shetland and Faroe Islands on the NE Atlantic Margin (Fig. 1). The basin can be sub divided into a series of SW-NE trending sub-basins and is contiguous with the Møre Basin to the north-east and the Rockall Trough to the south-west (Hitchen & Ritchie, 1987). The sub-basins consist of Jurassic to Recent sediments bound by basement highs comprised of Precambrian crystalline rocks (Lamers & Carmichael, 1999). The FSB has undergone several stages of rifting between the Devonian and Paleocene, followed by Late Paleocene and Mid-Miocene inversion (Smallwood & Maresh, 2002; Sorensen, 2003; Ritchie et al., 2011). The multiple-rifting events are thought to be influenced by a pre-existing NE-SW structural grain inherited from the Caledonian orogeny (Kimbell *et al.,* 2005) The main structure of the basin is further complicated by transfer lineaments which run perpendicular to the main SW-NE trend of the basin (Ellis *et al*., 2009; Moy & Imber 2009; Schofield & Jolley, 2013) (Fig. 1). There is considerable debate regarding the nature and origin of these lineaments (Moy and Imber, 2009), although most research agrees that they have played a part in influencing sediment deposition and could have acted as conduits for upwelling magma (Jolley *et al.,* 2005; Archer *et al.,* 2005; Ritchie *et al.,* 2011).

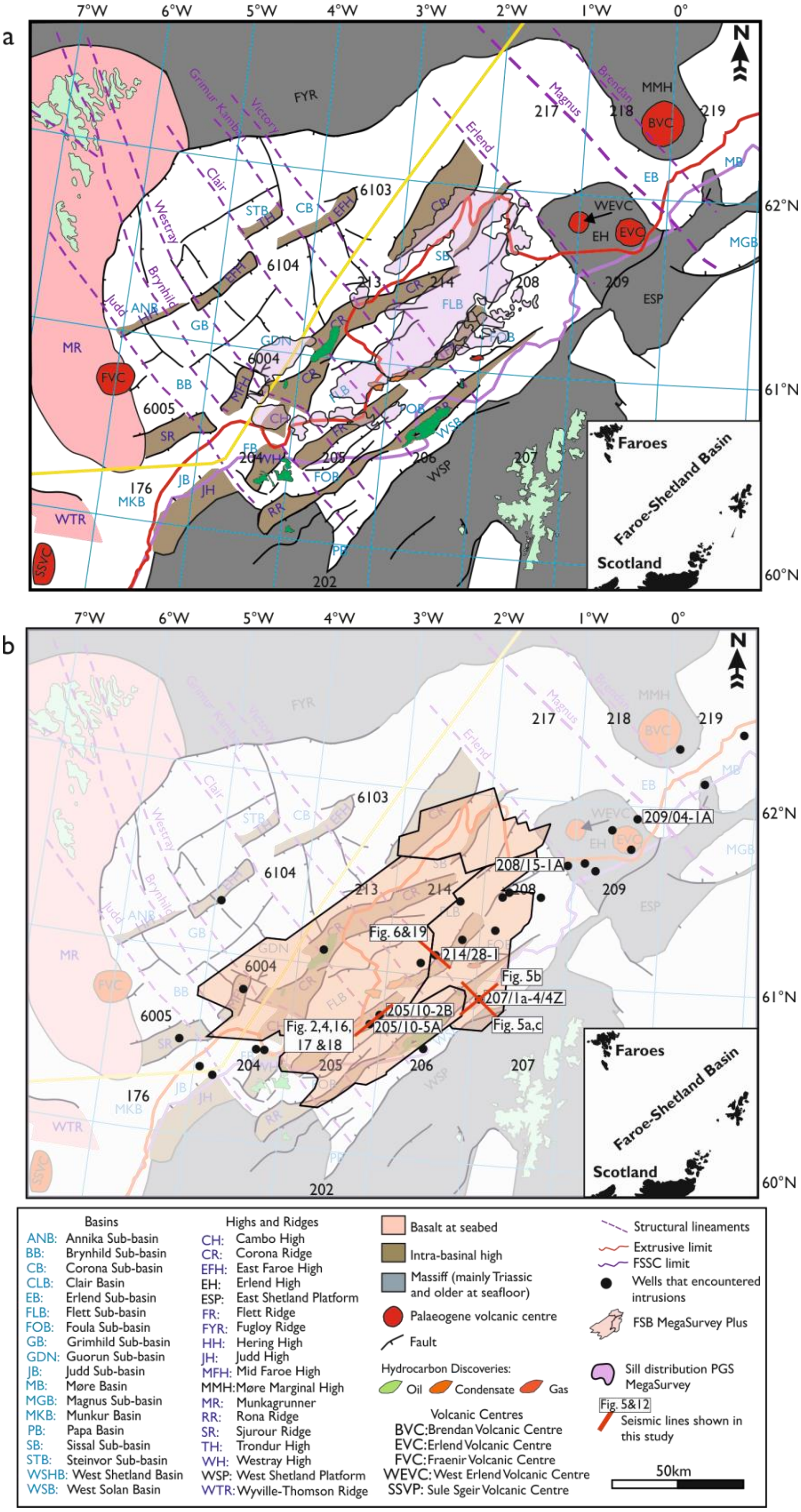

a
b
7°W
6°W
5°W
4°W
3°W
2°W
1°W
0°
62°N
61°N
60°N
N
Faroes
Faroe-Shetland Basin
Scotland
FYR
MMH
BVC
217
218
219
EB
MB
MGB
WEVC
EH
EVC
209
ESP
208
214
213
6103
6104
6004
6005
MR
FVC
204
205
206
207
202
176
WSP
WTR
SSVC
209/04-1A
208/15-1A
214/28-1
207/1a-4/4Z
205/10-2B
205/10-5A
Fig. 6&19
Fig. 5b
Fig. 5a,c
Fig. 2,4,16, 17 &18
Basins
ANB: Annika Sub-basin
BB: Brynhild Sub-basin
CB: Corona Sub-basin
CLB: Clair Basin
EB: Erlend Sub-basin
FLB: Flett Sub-basin
FOB: Foula Sub-basin
GB: Grimhild Sub-basin
GDN: Guorun Sub-basin
JB: Judd Sub-basin
MB: Møre Basin
MGB: Magnus Sub-basin
MKB: Munkur Basin
PB: Papa Basin
SB: Sissal Sub-basin
STB: Steinvor Sub-basin
WSHB: West Shetland Basin
WSB: West Solan Basin
Highs and Ridges
CH: Cambo High
CR: Corona Ridge
EFH: East Faroe High
EH: Erlend High
ESP: East Shetland Platform
FR: Flett Ridge
FYR: Fugloy Ridge
HH: Hering High
JH: Judd High
MFH: Mid Faroe High
MMH: Møre Marginal High
MR: Munkagrunner
RR: Rona Ridge
SR: Sjurour Ridge
TH: Trondur High
WH: Westray High
WSP: West Shetland Platform
WTR: Wyville-Thomson Ridge
Basalt at seabed
Intra-basinal high
Massiff (mainly Triassic and older at seafloor)
Palaeogene volcanic centre
Fault
Hydrocarbon Discoveries:
Oil
Condensate
Gas
Volcanic Centres
BVC: Brendan Volcanic Centre
EVC: Erlend Volcanic Centre
FVC: Fraenir Volcanic Centre
WEVC: West Erlend Volcanic Centre
SSVP: Sule Sgeir Volcanic Centre
Structural lineaments
Extrusive limit
FSSC limit
Wells that encountered intrusions
FSB MegaSurvey Plus
Sill distribution PGS MegaSurvey
Fig. 5&12
Seismic lines shown in this study
50km

Figure 1: a) Structural elements map of the Faroe-Shetland Basin, with mapped sill extent. b) Outline of 3D seismic coverage and wells penetrating intrusions used in this study. Figure adapted from Ellis *et al.,* 2009, Schofield *et al.,* 2015 Mudge, 2014.

The FSB, along with the NE Atlantic Margin, underwent considerable igneous activity during the Late Paleocene as a result of the impinging proto-Icelandic plume and the eventual continental break-up between Greenland and Northwest Europe (White & Mckenzie, 1989). This igneous activity caused eruption of thick extrusive basaltic sequences and the emplacement of a pervasive suite of sills and dykes, the majority of which are of basaltic composition and intrude mainly into the Cretaceous sediments (Gibb & Kanaris-Sotriou, 1998, Bell & Butcher, 2002, Thomson & Schofield, 2008, Schofield *et al.,* 2015, Schofield et al. 2017). The intrusions, collectively termed the Faroe-Shetland Sill Complex (FSSC), are found throughout the FSB with their areal extent following the SW-NE basin trend, extending northwards into the Møre basin and south into the Rockall Trough (Ritchie *et al.,* 2011) (Fig. 1). The intrusions are thought to have been emplaced between 55-53 Ma (Ritchie & Hitchen, 1996; Passey & Hitchen, 2011) although this has been questioned by recent work that suggests older phases of intrusions ranging from 61-58 Ma based on onlapping relationships onto forced folds (Schofield *et al.,* 2015). Forced folds are caused by the jack up of the overburden by intrusions during emplacement (Trude *et al.,* 2003).

DATA AND METHODOLGY

The data used within this study consists of the Faroe-Shetland PGS MegaSurvey Plus 3D seismic dataset (Fig. 1), which covers an area of 24,000 km^2. The data has undergone substantial reprocessing leading to clear imaging of the FSSC (Schofield et al. 2015). The well data includes all the released exploration and appraisal wells drilled in the FSB, which were analysed to identify igneous intrusions. Of this dataset, 29 wells encountered intrusions, the locations of which are highlighted in Fig. 1b. For these wells, all wireline data (e.g. p-wave compressional velocity, gamma ray), composite logs, drilling data (e.g. rate of penetration, weight on bit) and available core was synthesised and interpreted.

IDENTIFICATION OF INTRUSIONS IN THE SUBSURFACE: SCALE AND DATA BIAS

Identification of Intrusions in Seismic and Seismic Resolution

The majority of igneous intrusions seismically imaged in the FSSC have a basaltic composition (informed by geochemistry from cored intrusions Gibb & Kanaris-Sotriou, 1998) and are easily identifiable as bright, high amplitude reflectors that are laterally discontinuous and crosscut stratigraphy (Bell & Butcher, 2002; Smallwood & Maresh, 2002, Schofield *et al.,* 2015) (Fig. 2a). The high amplitude nature of the basaltic intrusions results from their high acoustic impedance relative to the surrounding host rock sediments (Fig. 2b), which is a product of their high density (2.8-3.0 g/cm^3) and sonic velocities (5.5-6.6 km/s) (Bell & Butcher, 2002; Smallwood & Maresh, 2002).

Schofield *et al,* (2015) & (2017) discusses the issues regarding the vertical resolution of seismic data and how, depending on the seismic tuning thickness, intrusions may be poorly resolved or not resolved at all, leading to a potential underestimation of intrusive volume within the Atlantic Margin Basins. Schofield *et al*, (2015) shows that for the Cretaceous succession in the FSB, where the majority of the intrusions of the FSSC are hosted, the vertical resolution ranges from 54m at the top Cretaceous to 81m at the base of the Cretaceous with detectability ranging from 26m to 40m.

Identification of Intrusions in Wireline and Wireline Resolution

Basic (basaltic) igneous intrusions have a characteristic wireline response making them distinguishable relative to the host sediments (Bell & Butcher, 2002: Smallwood & Maresh, 2002) (Fig. 2b). Although, identification of basic igneous intrusions is usually relatively simple from wireline log responses, it is important to understand the petrophysical properties of basalt which lead to this response; this is particularly important when understanding and contrasting the wireline response of other igneous rock types (e.g. acidic/evolved) within the subsurface.

Basic magma is abundant in minerals such as olivine and pyroxene, which have p-wave compressional velocities of 8420m/s and 7200 m/s respectively (Mavko *et al*., 2009; Rider & Kennedy, 2011). This leads to basic igneous intrusions having high compressional p-wave sonic velocities that are much higher than surrounding sediments and are typically within the range of 5.5-6.6 km/s (which converts to 55-45μs/ft which is the conventional unit of measurement for UK continental shelf wells) (Fig. 2b). Shear wave sonic velocities for igneous intrusions are also much higher than surrounding sediments and are typically within the range 2.4-3.4 km/s (Fig. 2b). Due to the typical uniform distribution of minerals through relatively thin igneous intrusions, the sonic wireline response is generally 'blocky' showing little to no variation through an intrusion (see Fig. 2b)

In addition to possessing high seismic velocities, olivine and pyroxene also possess high relative bulk densities of 3.31 g/cm^3 (olivine) and 3.3 g/cm^3 (pyroxene) (Mavko *et al.*, 2009; Rider & Kennedy, 2011), resulting in basic igneous intrusions typically exhibiting bulk densities between 2.8-3.0 g/cm^3 with a 'blocky' wireline response which is easily distinguishable from the background host rock sediments (Fig. 2b).

The neutron response for basaltic igneous intrusions is typically lower than the surrounding host rock sediments with values in the range of 0.08-0.1pu (Fig. 2b). The neutron log essentially measures the hydrogen content of a formation and will generally be low for a crystalline igneous rock as there is often limited pore space to host water (Rider & Kennedy, 2011). The neutron-density separation for basaltic igneous intrusions is typically a positive separation (neutron to left, density to the right) which is a larger positive separation than for shale sediments (Fig. 2b).

As basaltic magma generally contain few radioactive minerals (e.g. Potassium, Thorium and Uranium) the typical gamma response for basaltic intrusions is very low, in the range of 9-30 API.

Basaltic intrusions are significantly more electrically resistive than the surrounding host rock sediments (shales), as they have low porosity and permeability and contain little or no water compared with host rock sediments. The resistivity log for basaltic intrusions commonly shows wrap-around (when measured values exceed the upper range on the scale) due to the resistivity being so high. The resistivity log response is less blocky compared to the sonic density and gamma logs with a more serrated response (Fig. 2b). For some intrusions, the resistivity log can be chaotic and fluctuate significantly over a short distance which often reflects fracturing within the intrusions.

The caliper log measures the internal diameter of the borehole and therefore condition of the hole (Smallwood & Maresh, 2002). Due to the mechanically resistive and competent nature of intrusions, the caliper log typically remains uniform through intrusions in the FSB although if the intrusions are thin and fractured, they are more likely to collapse into the wellbore causing deviations in the caliper log.

Although gamma ray logs record a sharp change when an intrusion is encountered, resistivity, p-wave sonic and neutron-density logs show a gradual variation (Fig. 2b). Commonly this creates a bell shaped wireline response caused by the values ramping up or down in the host rock sediments directly above and below the intrusive contact (Fig. 2b). This ramping up of the values in the host rock prior to encountering the intrusion is interpreted as representing the contact metamorphosed or hornfels zone. This zone is where the host rock sediments have been altered by heating from the intrusions resulting in differing petrophysical characteristics compared to the unaltered host rock sediments (Smallwood & Maresh, 2002).

Despite wireline logs (e.g. Gamma, Neutron Porosity, Resistivity) often showing distinct log motifs upon recording igneous intrusions, wireline tools have limitations in terms of the vertical thickness of beds and bed properties the tools can actually resolve.

Table 1 lists the various wireline logs and their average vertical resolution, although this figure can vary depending on factors such as logging speed and formation properties. Over non-reservoir intervals which are of less commercial interest, logging speeds will be faster, and often with a reduced suite of tools, which can lead to reduced ability to distinguish individual bed boundaries. However, at best, intrusions which are <1m thick are unlikely to be distinguished using the common logging tools. Modern downhole well tools such as borehole imaging logs have a much greater vertical resolution (2 mm); however, due to cost, these are typically reserved for reservoir sections and are often not run across the full drilled section.

Logs	**Definition**	**Response in Basaltic Intrusions**	**Vertical Resolution**

Gamma	Measures the radioactivity of the formations	Sharp drop (9-30 API)	60-90cm
Resistivity	Measures the resistivity of the formations	High blocky response but can also be serrated with big fluctuations (250-1000 ohm.m).	Induction tools: 100cm
Neutron Density	Measures a formations water content	Lower than surrounding sediments and blocky response (0.08-0.1pu)	40-60cm
Bulk Density	Measures the overall density of the rock	Higher than surrounding sediments and blocky response (2.8-3.0 g/cm$^{3)}$	40-60cm
Sonic	Formations interval transit time	Acoustically faster than surround sediments, blocky response (5.5-6.6km/s)	60cm
Caliper	Measures the diameter of the well bore	Consistent but fractures can cause deviations	N/A

Table 1: General petrophysical response for different logging tools (Rider & Kennedy, 2011).

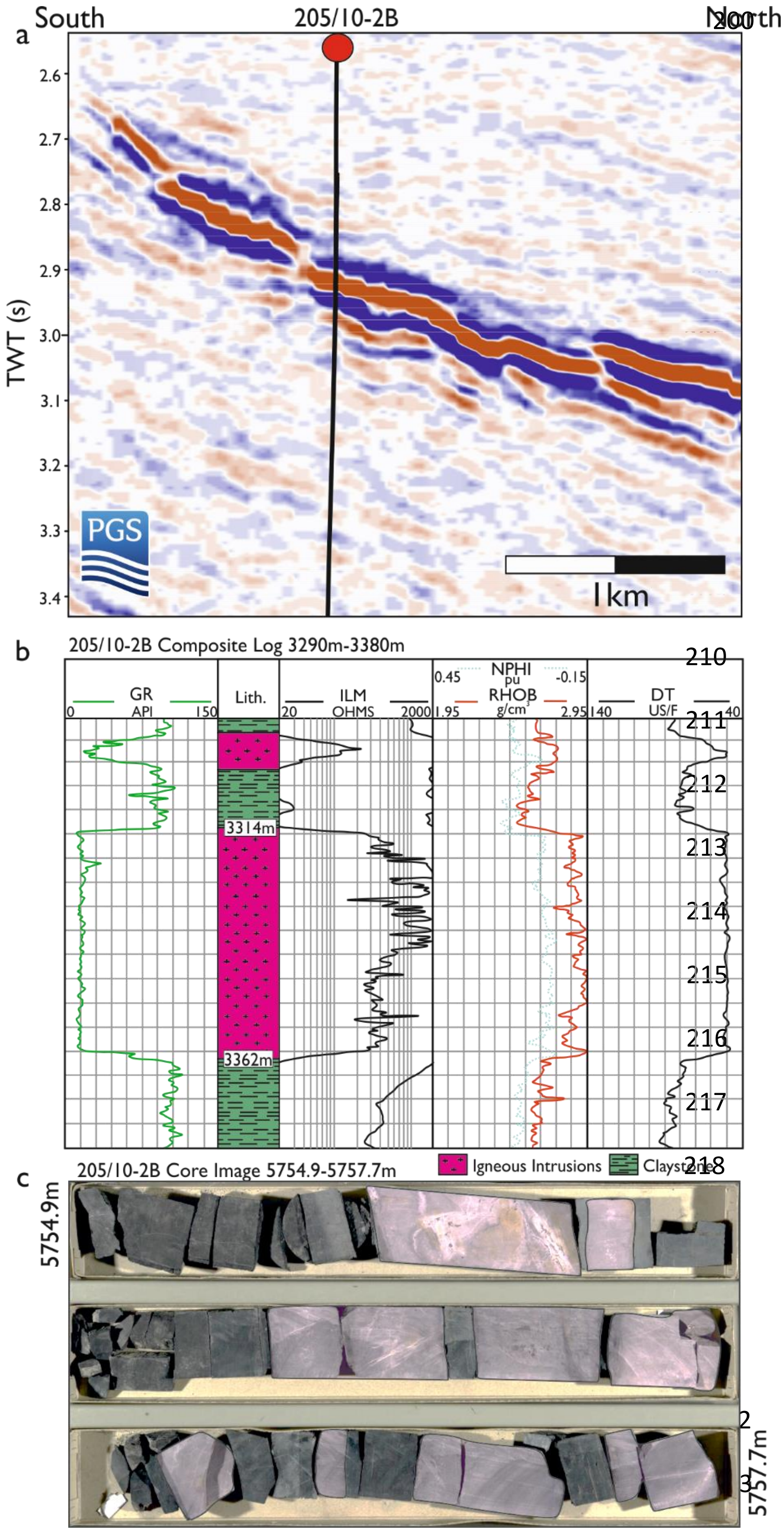


Figure 2: a) Typical seismic response of basaltic intrusions in the FSSC. Intrusion is 47m thick. b) Characteristic petrophysical response of basaltic intrusions. c) Core of thin basaltic intrusions into Cretaceous shales from the 205/10-2B well, core image courtesy of BGS offshore database (BGS 2017). Seismic data courtesy of PGS (PGS FSB MegaSurvey Plus).

Identification of Intrusions in Core & Cuttings

Well cuttings are a product of the drilling process and are small pieces (<0.5-10 mm) of rock that are broken away by the drill bit during the drilling process, are analysed at the rig site and are given a geological description (Cook *et al.,* 2012). Cuttings are ideally sampled every 10ft, but this may depend on the well design and drilling performance, although often sample rate increases when the well reaches the prognosed reservoir interval (Millet *et al.,* 2016). Cuttings from sub-aerially erupted extrusive basalt are generally weathered and altered due to subareal exposure, and are also more likely to contain vesicles and glassy material (Millet *et al.,* 2014). In contrast, cuttings from intrusives are generally coarser grained, possess fewer vesicles and have a 'fresh' unweathered appearance (Millet *et al.,* 2014).

If core is acquired during drilling, it is possible to categorically define that an intrusion has been encountered. Visually, intrusions can be identified in the core data as they differ in texture and appearance (Fig. 2c). Although core data is useful, it is usually only acquired for reservoir sections and any intrusions that are cored within the UKCS have often been done so serendipitously.

Core through intrusions allows the identification of intrusions which are < 10 cm in thickness, greater detection than would be possible with any of the common logging tools.

As an illustration of intrusion detectability in wireline and core, the original composite log for well 205/10-2B (Fig. 2c) only interpreted two intrusions at the base of the well. However, this section was also cored and actually contains 15 thin intrusions ranging from 4-30 cm in thickness with a cumulative thickness of 2.5m.

Drilling Data

Measurements recorded during drilling (MWD) such as rate of penetration (ROP), torque and weight on bit (WOB), can also be used to identify intrusions in the subsurface. These measurements are acquired whilst the well is being drilled and are measured continuously with minimal lag time, therefore they provide the first indication of the presence of an intrusion within the subsurface. Even logging measurements acquired whilst drilling (LWD), located downhole on the bottom hole assembly, possess a delay when compared to live drilling measurements as these tools are commonly located around 10 m from the drill bit, meaning that an intrusion could have already been penetrated before it is picked up on logs.

When drilling through intrusions, it is common for the ROP to drop to values as low as <1-2 m/hr, whereas shales have values around 5-20m/hr and sandstones typically have values 20-30m/hr. The ROP values for different sediments is highly variable due to factors such as weight on bit, drill bit type and drilling depth; however, igneous material typically drills much slower than sediments (Fig. 3). Additionally, due to the hard nature of crystalline rocks, bit degradation can rapidly increase.

The WOB measures the amount of downward force exerted on the bit during drilling. Due to the hardness of intrusions, ROP can drop significantly; to counteract this, the driller will increase the WOB to maintain high ROP (Fig. 3).

If drilling through an igneous intrusion, the WOB and rotations per minute (RPM) of the drill bit are not closely controlled, the drill head can become stuck and 'lock-up', resulting in increasing torque on the drillstring. If torque on the drillstring continues to increase to critical levels, it can cause 'twist off' of the drillstring from the bottom hole assembly in the well bore.

As igneous intrusions commonly contain cooling fractures, are brittle and therefore susceptible to further fracturing during later tectonic movements, issues can also occur with loss of drilling mud (used to maintain wellbore integrity and to prevent an influx of pressure and fluids into the wellbore). Loss of drilling mud is not only costly, but the mud is also crucial to maintaining stable downhole conditions, cuttings return and importantly, control the potential influx of fluids into the wellbore.

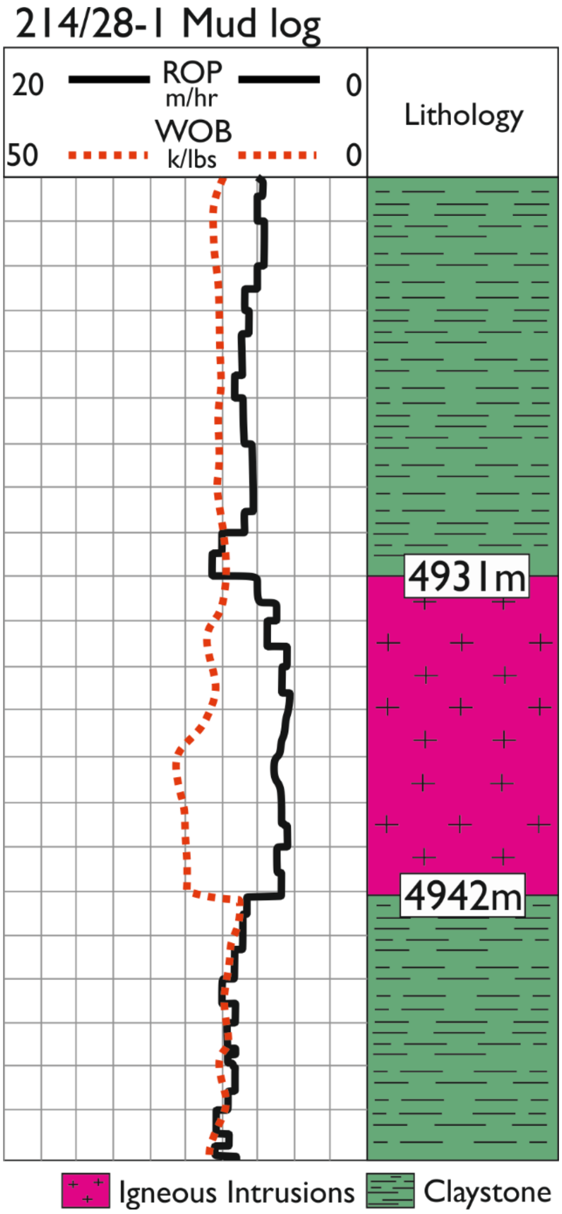


Figure 3: Typical ROP and WOB response drilling through igneous intrusions in the 214/28-1 well.

FSB INTRUSIONS STATISTICS

From statistical analysis of the intrusions encountered by wells in the FSB, it is possible to gather data about the intrusions and their various characteristics such as abundance and average thicknesses (Schofield *et al.,* 2015). In total, 251 intrusions have been identified in the FSB wells based on log descriptions, petrophysical response and where possible, seismic to well ties.

It has been possible to determine the following about the FSSC:

- Average intrusion thickness: 14.9 m (minimum thickness: 6 cm and max thickness: 277 m)

- Average depth of intrusions: 3579 m true vertical depth subsea (TVDSS). (shallowest: 1709 m and deepest: 5755 m)

- Claystone is the most common host rock lithology with 245 of the 251 total intrusions emplaced into claystone/shale.

- 8% of intrusions encountered are evolved. These evolved compositions range from diorite to rhyolite and have a higher silca content.

- 75% of intrusions encountered occur in Cretaceous sediments.

- 24% of intrusions encountered occur in Palaeocene sediments.

- 1% of intrusions encountered occur in Jurassic sediments (this figure is highly biased due to few wells penetrations in the Jurassic– see discussion below)

The above statistics, however, need to be taken in context of the data bias as exploration wells are typically situated away from areas that contain a large number of seismically resolvable intrusions. However, in terms of average thickness, when the well results are compared against wells which have accidentally targeted areas of high intrusion density (e.g. 164/7-1 in the Rockall Basin which encountered 76 intrusions over an 1800m thick interval; the average thickness is 11m Archer *et al.,* 2005) the average thickness value of c. 15m appears to be a reasonable estimate for offshore basins along the Atlantic Margin.

In terms of the stratigraphic successions which host the most intrusions, factors like total depth of the well will affect whether intrusions are present or not. From both well and seismic data, it is clear that intrusions are prevalent throughout the Cretaceous succession. However, well penetrations of older successions in basinal settings (e.g. Jurassic) are limited within the FSB (Fig. 1) and tend to be focused along the basin margins (e.g. Judd High and Erlend High) where there are fewer intrusions, therefore introducing a strong sampling bias. Despite this, the fact that intrusions have been sampled within the Jurassic, even on basin highs, suggests that the percentage of intrusions in basinal area of the Jurassic (and older strata) is likely to be much higher than the 1% based on the current well data.

The data is also biased towards intrusions ranging in thickness below 50 m, as intrusions thicker than this will generally be visible on seismic data and therefore likely to be avoided during drilling activities

(Schofield et al. 2015). A further bias also exists based on the age of the well since increased knowledge about the basin through drilling activity increases the chance of recognising igneous bodies within seismic data, and de-risks the likelihood of accidentally encountering them (Table 2). Continued future improvements in seismic data will likely reduce the number of igneous intrusions encountered in exploration wells by virtue of better detectability (Schofield *et al.,* 2015).

Time Period	Number of Exploration Wells that Encountered Intrusions	Number of Intrusions encountered by exploration wells	Average Thickness of Intrusions
1970-1980	3	20	16.8
1980-1990	12	170	14.5
1990-2000	6	7	52.9
2000-present	8	40	14.5

Table 2: Intrusion statistics over time. The increase in the number of intrusions encountered during the 2000-present period is likely a result of companies targeting sub-basalt prospects, particularly in the Faroes sector (e.g. Brugdan) with the extrusive basalt making it difficult to image intrusions.

FSB EXPLORATION CASE STUDIES 1: ISSUES WITH EVOLVED INTRUSIONS AND SEISMIC IMAGING

To understand the challenges caused by encountering igneous intrusions in the subsurface, it is important to summarise some of the key wells and the issues that occurred related to igneous intrusions. The summary below, of a number of key wells, was compiled from composite logs, drilling reports and seismic data.

Wells 205/10-2B and 205/10-5A - Evolved Intrusions

The majority of intrusions within the FSSC that have been encountered in drilling operations have a basaltic composition and are described as tholeiitic olivine-dolerites (Gibb & Kanaris-Sotiriou, 1988; Ritchie *et al.,* 2011). However, several of the exploration wells have also encountered more evolved intrusions ranging from dioritic to rhyolitic compositions. Although some of the more evolved intrusions were encountered close to igneous centres (e.g. Erlend Igneous Centre wells 209/03-1, 209/04-1A and 209/09-1A; Jolley & Bell, 2002), exploration wells that were drilled in more basinal locations away from known volcanic centres also encountered more evolved intrusions (Fig. 1). Wells 205/10-2B drilled in 1984 by Britoil and 205/10-5A drilled in 1997 by Chevron located along the Flett Ridge (Fig. 1), encountered evolved intrusions with compositions varying from dacite to rhyolite.

The evolved intrusions in 205/10-2B occurred within a series of stacked basaltic intrusions, whereas the evolved intrusion within 205/10-5A was the only intrusion encountered within that well. Figure 4 shows the log and seismic response for the evolved intrusions encountered within the 205/10-5A and 205/10-2B in comparison to the log response for a basaltic intrusion encountered in 205/10-2B. Figure 4 illustrates the petrophysical and seismic imaging contrasts between evolved and basaltic intrusions. Notably, the evolved intrusion in 205/10-2B is acoustically similar to the host rock shales and the density also drops compared to the host rock shales. The gamma response is lower that the surrounding shales but is not as low as the basaltic intrusions encountered by 205/10-2B (Fig. 4a). The evolved intrusion in 205/10-5A also has a lower density compared to the host rock shales, whereas the gamma ray log shows minimal changes between the host rock and the intrusion (Fig. 4b & c). The significance of these petrophysical differences and the issues of identification of evolved intrusions within the subsurface is discussed later.

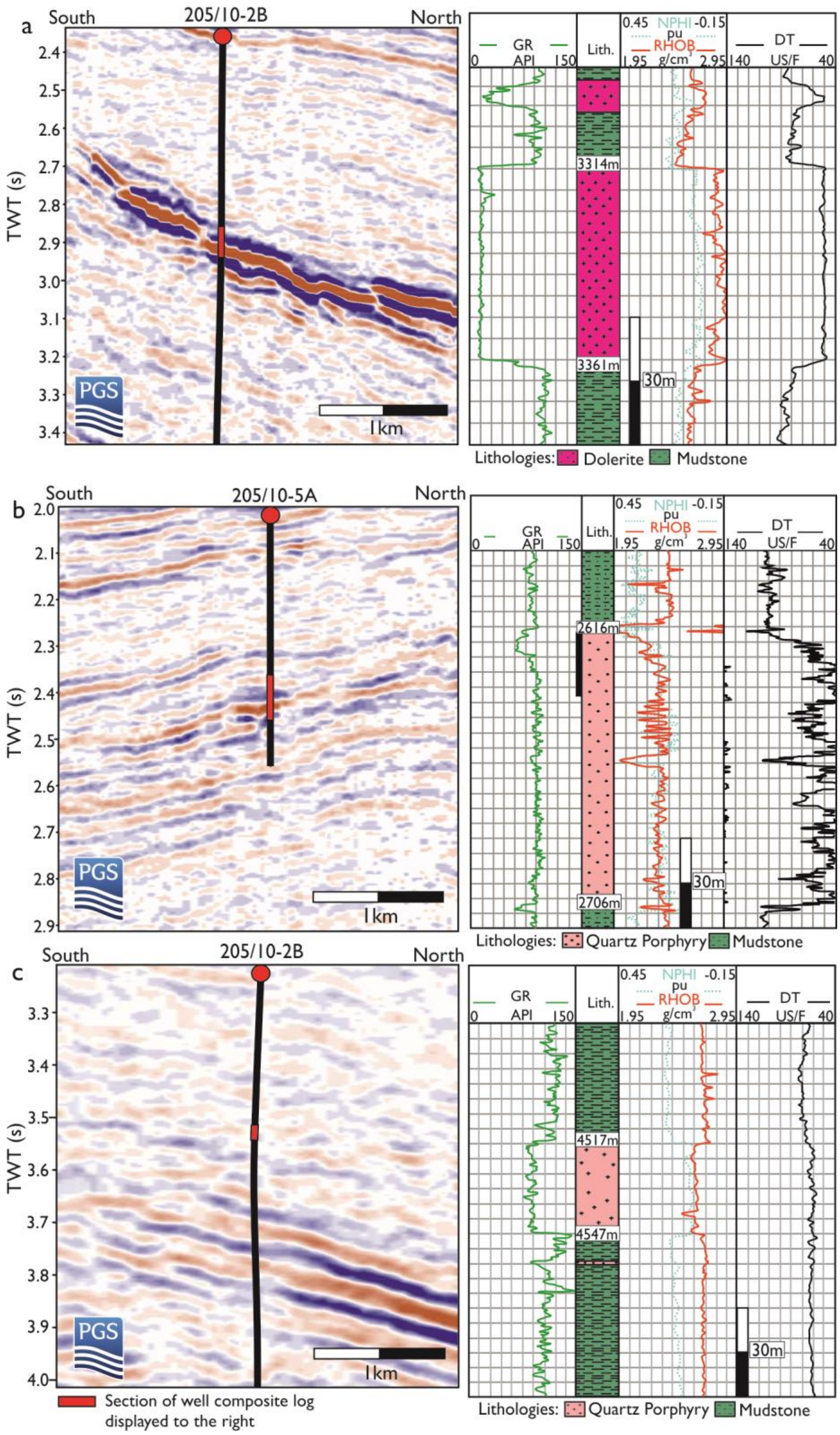


Figure 4: Petrophysical and seismic imaging contrasts between basaltic intrusions and evolved intrusions. a) 47m thick basaltic intrusion encountered in 205/10-2B. b) 90m thick evolved intrusion encountered in 205/10-5A. c) 30m thick evolved intrusion encountered in 205/10-2B. Seismic data courtesy of PGS (PGS FSB MegaSurvey Plus).

207/01a-4/4Z - False Exploration Targets

Well 207/01a-4 was drilled on the Rona Ridge in 1990 by Texaco Britain Ltd (Fig. 1). The reservoir targets were sediments deposited on the flanks of the Rona Ridge including Carboniferous/Devonian sandstones, Jurassic sandstones and Lower Cretaceous sandstones. These targets were not encountered during drilling; however, the top of a 213 m thick basaltic intrusion was encountered at 1584 MDBRT, 25m deeper than the first prognosed reservoir horizons were expected to occur. Upon penetrating the intrusion, the decision was taken to core the intrusion to determine what the lithology was. A virtual seismic profile (VSP) look ahead was also conducted, which showed that the intrusion was potentially 198m thick. Based on the results of core and the VSP log, the decision was made to sidetrack the well at a depth of 618mBRT downdip to the SE (207/01a-4/4Z End of Well Report).

The well drilled for a further 1369m before encountering the intrusion again at a depth of 1987 MDBRT. The sidetracked well drilled the entire intrusion, which was 213m thick. At the time of drilling, it is likely that the intrusion was poorly imaged on seismic data and the intrusion's close proximity to the Rona Ridge would make it difficult to distinguish a high amplitude intrusion from a high amplitude basement reflector. Seismic data at the original well location reveals that the well penetrated the intrusion, and then the sidetracked well (207/01a-4Z) was drilled to avoid the intrusion but simply encountered the deeper southern wing of the intrusion (Fig. 5).

Upon entering the intrusion, ROP in both the original and sidetracked well dropped from 25m/hr to 2m/hr; additionally, there were issues with bit wear (207/01a-4/4Z Geological Report). In the case of the 207/01a-4/4Z sidetrack, this resulted in the drilling of an undergauge hole, that subsequently required reaming to prevent the drill string becoming stuck, resulting in further NPT.

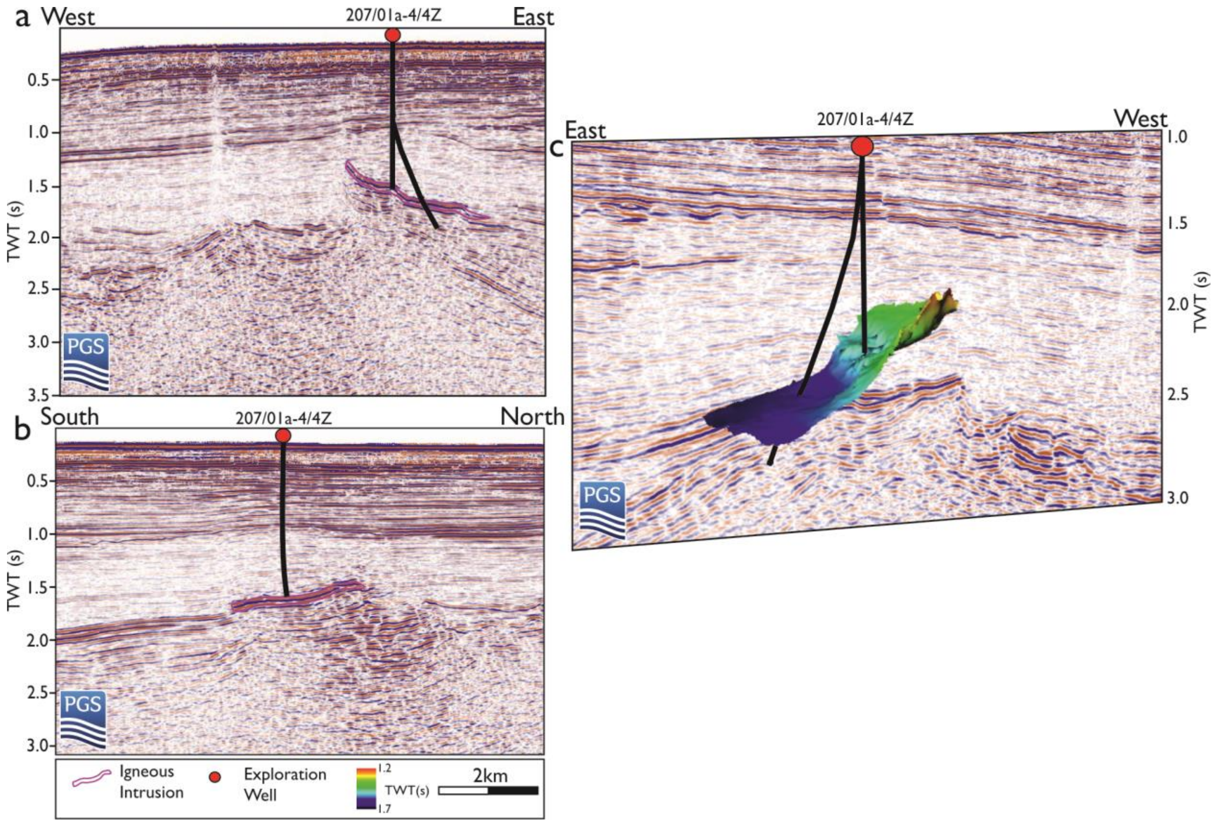


Figure 5: a) Seismic cross line showing the intrusion encountered in the 207/01a-4 well, b) seismic inline across the intrusion encountered in the 207/01a-4 well. In this line, the intrusion is less obvious and looks concordant with Rona Ridge high amplitude reflector, c) 3D image of the horizons interpretation of the top surface of the intrusion illustrating how the sidetrack encountered the lower wing of the intrusion. Seismic data courtesy of PGS (PGS FSB MegaSurvey Plus).

FSB EXPLORATION CASE STUDIES 2: DRILLING ISSUES ASSOCIATED WITH INTRUSIONS

Wells 214/28-1 - Drilling Issues (Gas Kicks and Bit Integrity)

Exploration well 214/28-1, drilled in 1984 by Esso Exploration and Production UK, encountered a total of 9 intrusions between 3816 and 5020m MDBRT (measured depth below rotary table) in Lower Paleocene and Upper Cretaceous sediments (Tassone et al. 2014). These intrusions resulted in numerous drilling issues towards the lower half of the well, most notably the penetration of a series of gas charged intrusions between 4598-5014m MDBRT, which led to the temporary loss of well control and drilling fluids being ejected out of the well onto the kelly bushing and rig floor (Fig. 6).

Well 214/28-1 also experienced problems with drill bit integrity and low ROP. Six drill bits were required to drill a 322m section in the Middle Paleocene which contained four intrusions with a combined thickness of only 52m, whereas a similar 400m sedimentary section with no intrusions in the nearby 214/27-1 offset well required only 3 drill bits.

The largest intrusion encountered in the 214/28-1 well occurred at 3992m MDBRT and was 44m thick. This intrusion had ROP of less than 1.5m/hr, whereas the host rock sandstones had ROP values of 3-6m/hr. Despite the thickness of this intrusion and the benefit of modern 3D seismic data, the intrusion is extremely difficult to fully image (Fig. 6).

The sixth deepest intrusion encountered at 4596m MDBRT was 6m thick and was one of the two intrusions within the well that was gas charged and required drilling to be stopped whilst the well was circulated to bring the gas influx under control. During this process, the mud weight was raised from 10.7 pounds per gallon (ppg) to 13.2 ppg which brought the gas influx in the well to acceptable levels. In total, this intervention incurred 15 days of non-productive time (NPT) and also resulted in the premature setting of the 7" liner which ultimately meant the well was unable to reach its intended TD (Fig. 6).

The eighth deepest intrusion encountered at 4927m MDBRT was 10m thick and resulted in extremely low ROPs which dropped from 2.5m/h through shales to 0.3m/hr through the intrusion. When the bit was pulled, it was found to be highly worn with a considerable amount of metal shavings found in the drilling mud. A new bit was deployed, but slow ROP continued through the intrusion with only 13m drilled in 34 hours (Fig. 6).

The ninth and deepest intrusion encountered in the 214/28-1 well occurred at 5013m MDBRT and was 7.6m thick. This intrusion was also found to be gas charged and the resulting influx of gas into the well bore resulted in mud flowing out over the kelly bushing. Drilling ceased and the well was shut in, whilst the mud weight was raised again, to 14.3 ppg. Although the mud weight was sufficient to control the pressure of the influxing gas, the high mud weight also led to mud losses. These losses were likely the result of induced fracturing of the surrounding host rock strata. This incident resulted in a total of 7 days of NPT whilst the gas levels were monitored (Fig. 6).

In total on well 214/28-1, the issues with gas charged intrusions and drill bit integrity resulted in a combined NPT of 22 days on top of the slow drilling rates (Fig. 6). The presence of the 9 intrusions was unexpected in the pre-drill scenario and the efforts to control the gas charged intrusions resulted in a premature termination of the well before it had reached its intended exploration target.

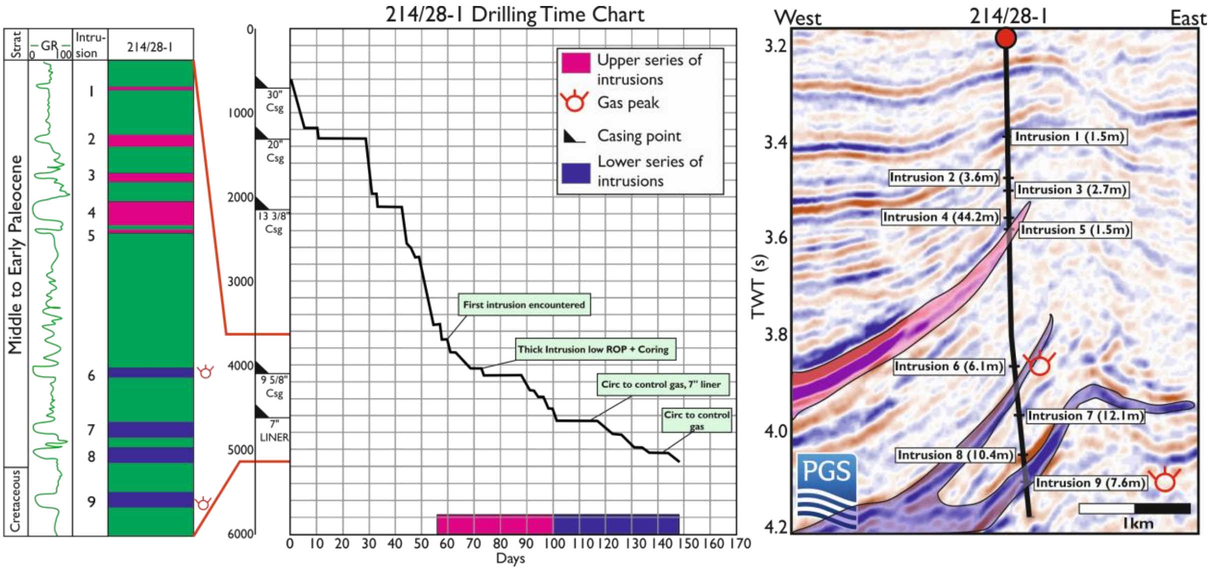


Figure 6: From left to right: composite log from 214/28-1 which encountered 9 dolerite sills; drilling chart from 214/28-1 showing the drilling issues encountered whilst drilling the sills; seismic line showing the amplitudes associated with the sills. Seismic data courtesy of PGS (PGS FSB MegaSurvey Plus).

Well 214/23-1 - Loanan Case Study

The Loanan prospect (214/23-1) was drilled in 2016 by JX Nippon Exploration & Production (U.K) Ltd (Fig. 7). The prognosed primary and secondary reservoir targets were Middle Paleocene turbidite reservoirs. Importantly, the closest offset well to Loanan is 214/28-1, which as described above, experienced significant problems whilst drilling due to the presence of igneous intrusions.

The Loanan primary target was within a structural closure, located at the edge of a forced fold (Schofield et al. 2015), and located 0.35s TWT (~600m's) above a large sill that was the continuation of the sills encountered in the 214/28-1 exploration well (Fig. 8). The secondary target was located 300m deeper, approx. 0.155s TWT (~260m) from the imaged top of the sill.

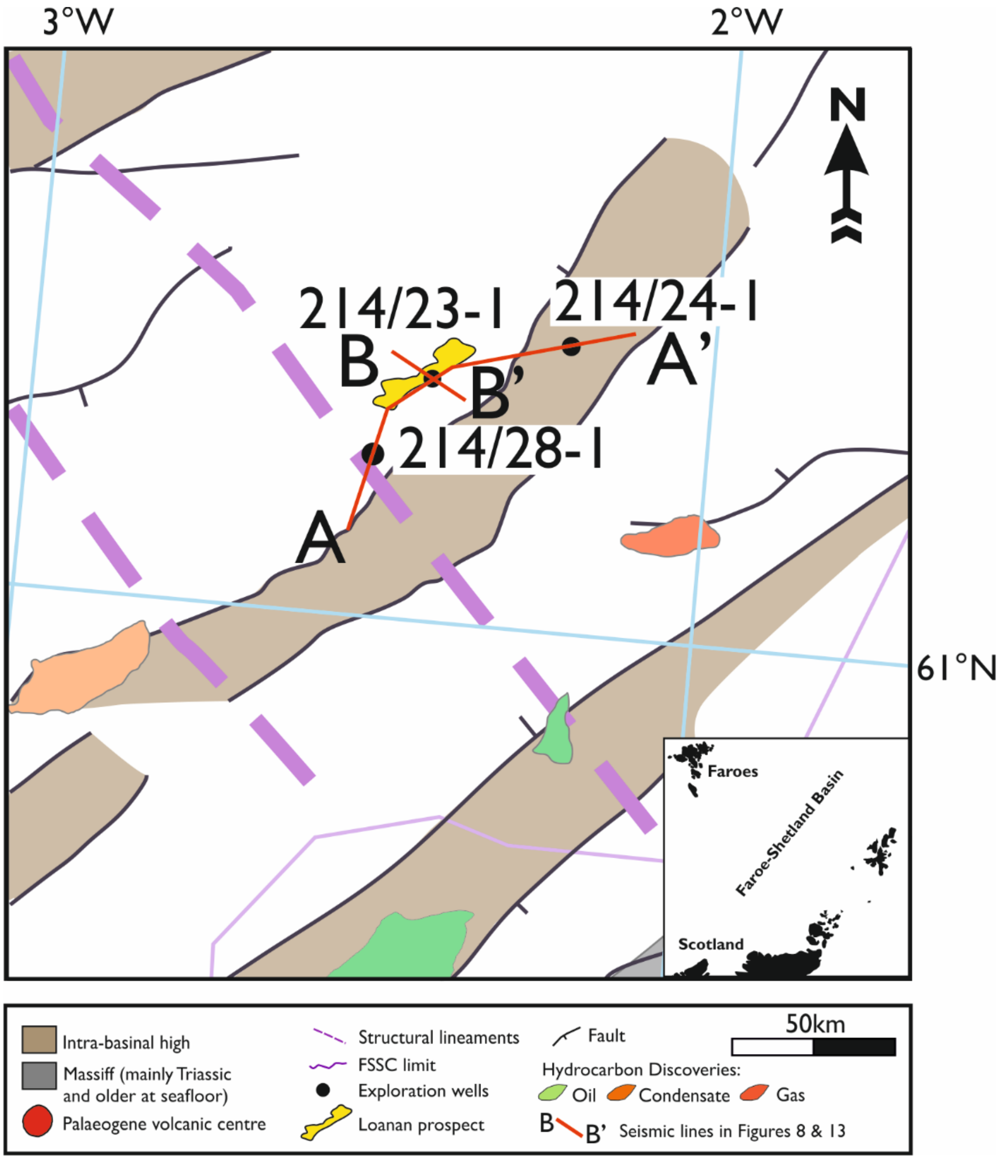


Figure 7: Map showing the location of the Loanan prospect relative to 214/28-1 which encountered overpressured intrusions.

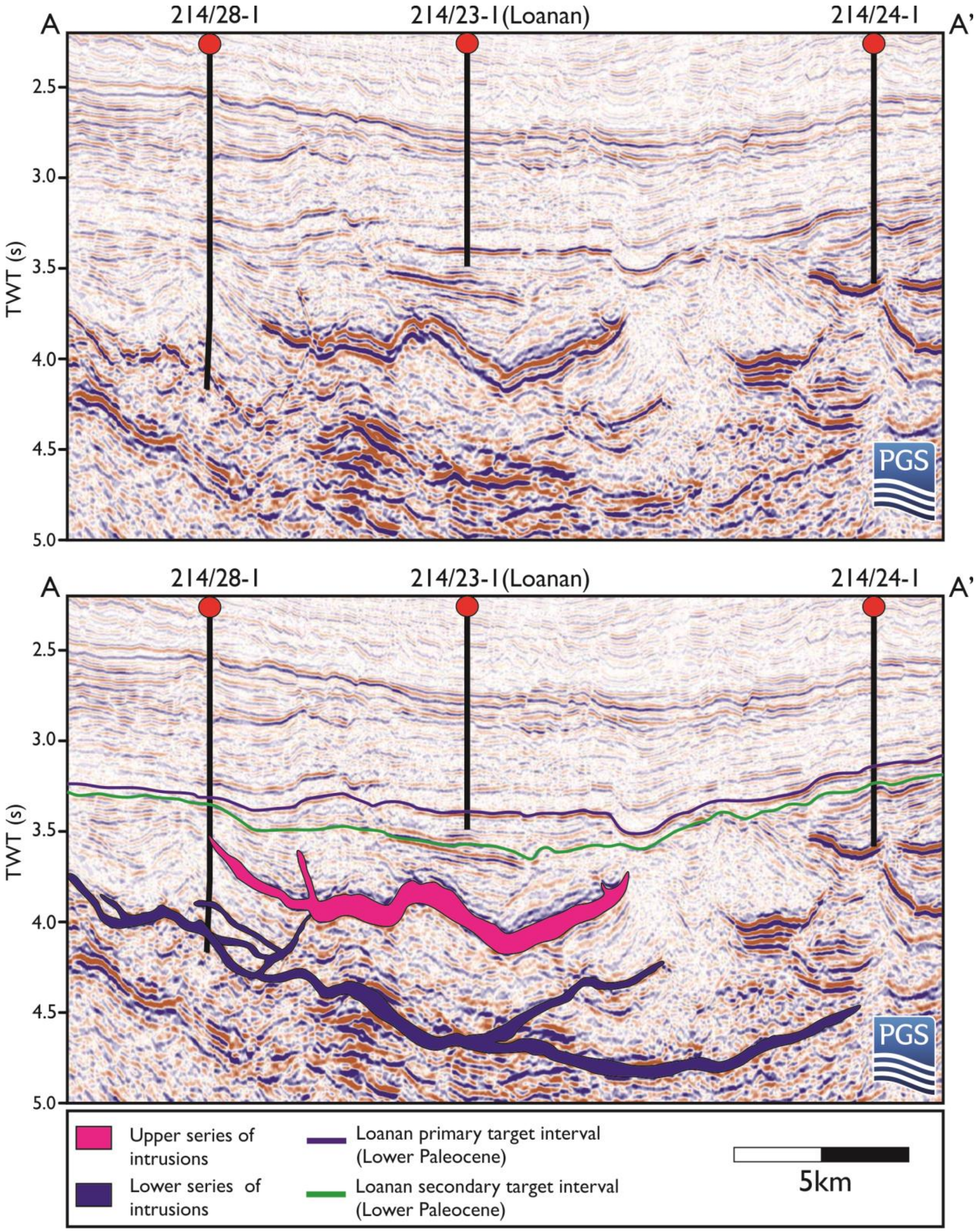


Figure 8: Arbitrary seismic line showing the Loanan target and its location relative to sills encountered in 214/28-1, which caused problems during drilling. Seismic data courtesy of PGS (PGS FSB MegaSurvey Plus).

During the well design process, concern had been expressed about encountering potentially overpressured intrusions, specifically in the secondary target, based on the offset well 214/28-1.

Although the planned TD for the Loanan was located some 400 metres above the stratigraphic level containing intrusions which caused the drilling issues in 214/28-1, seismic data appeared to image a series of cross-cutting intrusions potentially connecting the 'family' of intrusions which caused problems in the 214/28-1 well to the large intrusion which sat below the Loanan secondary target. On close inspection of the seismic data, it appears that thin intrusions, below the tuning thickness, potentially intrude the secondary Loanan target (Fig. 9)

Given the historical risk in offset wells and the uncertainty in encountering intrusions, particularly towards the base of the well, the well design catered for the small, but not negligible risk of encountering an overpressured, gas charged sill.

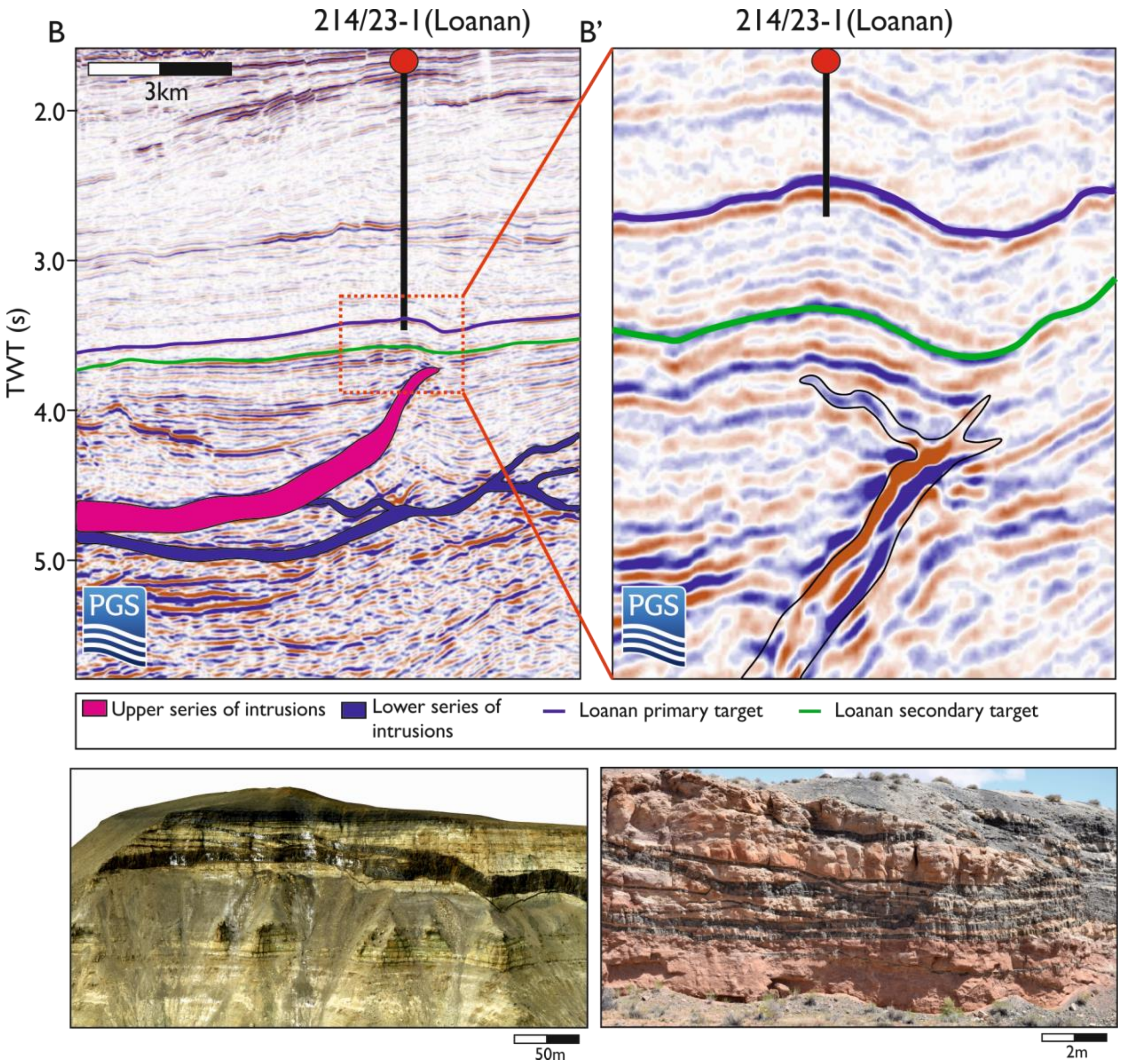


Figure 9: Seismic line showing the proximity of the Loanan target to the large sill beneath. Seismic line on the right shows the potential that there are small offset intrusions bifurcating from the large

intrusion towards the Loanan secondary target. There could also be additional smaller intrusions which are not seismically resolvable. Small bifurcating intrusions emanating from a larger intrusion is seen in outcrop on Jameson Island, East Greenland (modified from Eide *et al.,* 2017) and the San Rafael, Utah. Intrusions splays are a common feature in siliciclastic units (Eide *et al.,* 2017). Seismic data courtesy of PGS (PGS FSB MegaSurvey Plus).

In line with pre-drill expectations, the Loanan well encountered no intrusions near the primary target. Importantly, in addition to this, the leak of test (LOT) taken below the 9 5/8" shoe (146m above the top of the primary reservoir) was significantly lower than expected, suggesting that the rock formation was weaker then prognosed in pre-drill estimates. After the primary target had been penetrated, a second LOT was conducted to assess whether drilling could safely proceed given the concern of encountering an overpressured intrusion. The result of this LOT was 13.48ppg equivalent mud weight (EMW), again significantly below pre-drill estimates and lower than the previous LOT conducted 147 m above the primary target. This low LOT was deemed insufficient to provide adequate kick tolerance should an overpressured intrusions have been encountered deeper in the section towards TD. The decision was therefore taken to prematurely TD'd the well, short of the secondary target (Fig. 10) (214/23-1 End of Well Report).

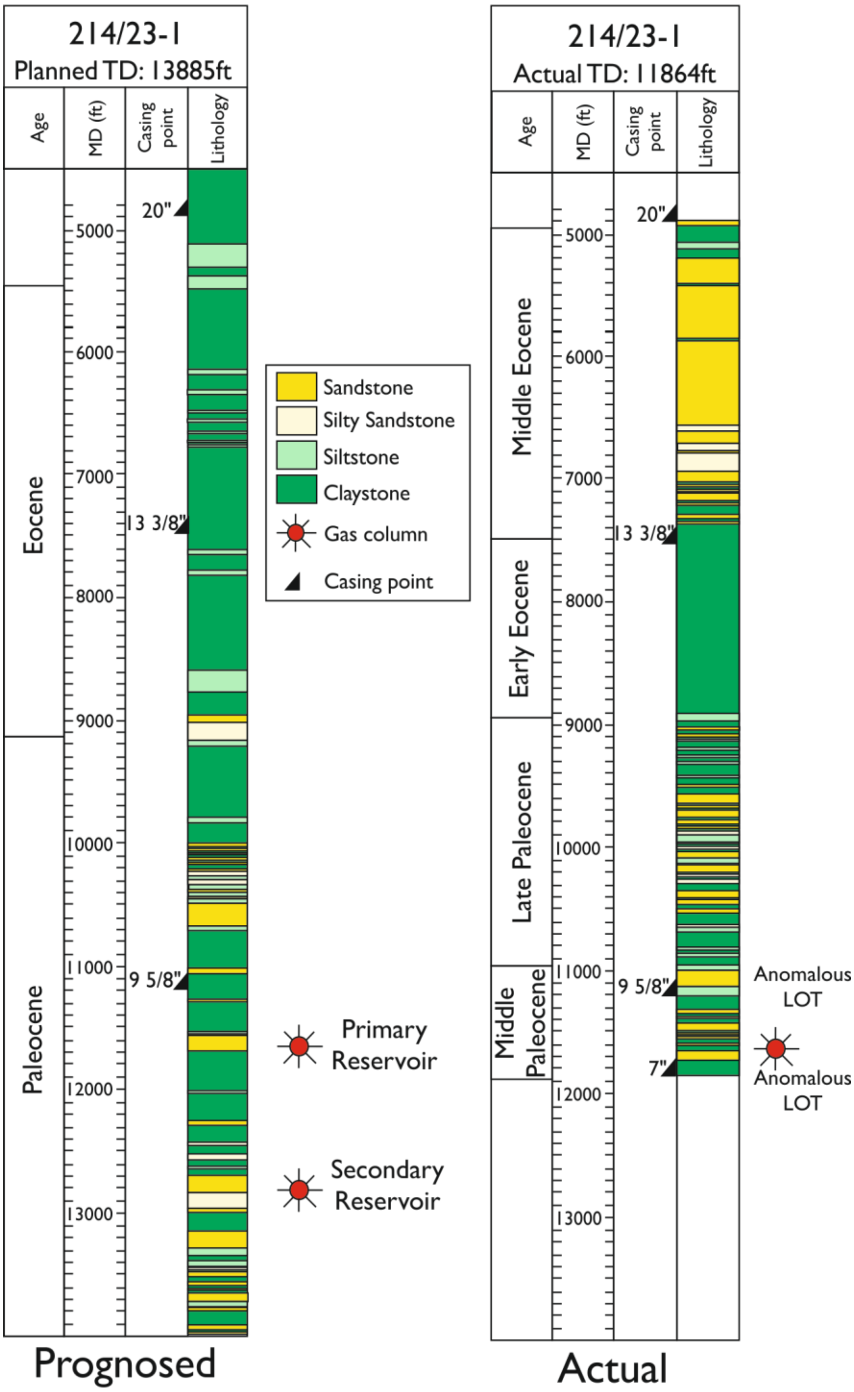


Figure 10: Prognosed vs actual stratigraphy of the Loanan well. The well was prematurely TD as a result of the anomalously low LOT below the 9 5/8" and 7 5/8" shoe. Modified from 214/23-1 End of Well Report.

Well 209/04-1A - Drilling Issues (Overpressure)

Well 209/04-1A drilled in 1985 by North Sea Sun Oil Co was drilled on the Erlend High near to the Erlend Volcanic Centre. This well encountered a series of evolved intrusions and also a series of basaltic intrusions. At a depth of 3085m MDBRT, a sudden lithology change from a thick rhyolitic intrusion to Upper Cretaceous claystone subsequently lead to an increase in the pore pressure. This increase in pore pressure required the mud weight to be raised from 8.7 ppg to 10.8 ppg to contain the pore pressure increase, although, like 214/28-1, this also resulted in mud losses (Fig. 11).

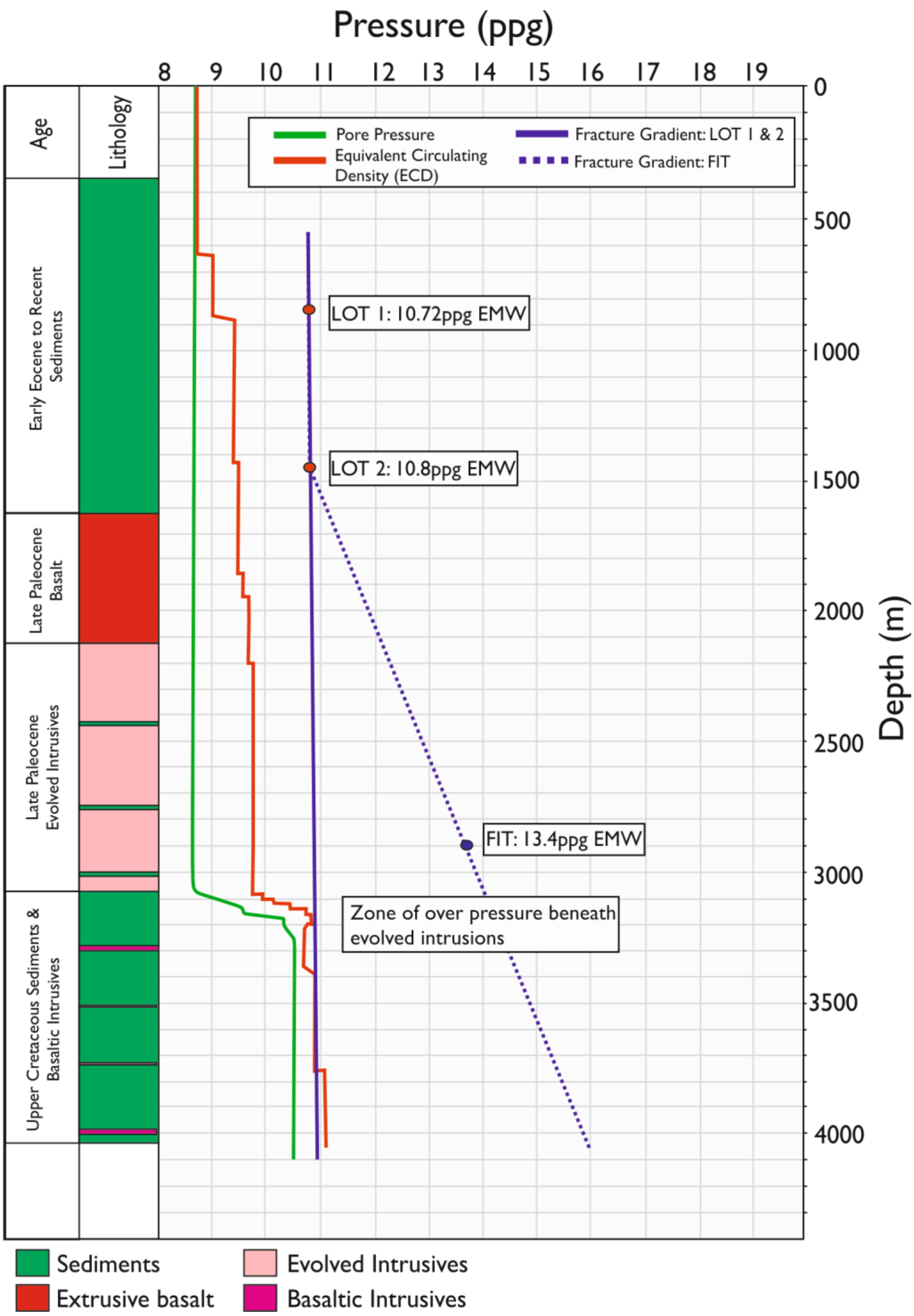


Figure 11: Pore pressure chart for the 209/04-1A well. The chart shows the sudden increase in pressure when drilling out of the evolved intrusions into the underlying claystones and the need to raise the ECD to mitigate this. However, raising the ECD resulted in mud losses.

Well 208/15-1A – Drilling Issues (Mud Losses and Wireline Running Issues)

Well 208/15-1A, drilled in 1979 by BP, encountered 7 basaltic intrusions in the Lower Paleocene succession between 1923m to 3123 MDBRT, with a range between 2.5m to 100m in thickness. A 60 m thick intrusion encountered at 1935 MDBRT incurred significant mud losses. The losses within this single intrusion were classed as severe and ranged from $3m^3$/hr (18bbls/hr) to $20m^3$/hr (126bbls/hr) and eventually resulted in total loss of circulation (208/15-1A End of Well Report). During this period, drilling was continued although the lithology log had to be determined based on ROP alone as there were no cuttings returned to the surface. In total, 23,000bbls (approx. 3.6 million litres) of mud where lost drilling the 1.2km section containing the seven intrusions, with losses as high as $60m^3$/hr (377bbls/hr) (208/15-1A End of Well Report). To maintain well control whilst drilling through the 60 m thick intrusion, seawater had to be pumped down the wellbore to maintain a static annulus, which resulted in a well which was out of balance. In an attempt to deal with the mud losses, loss of circulation material (e.g. bark, mineral fibre, hair, mica flakes, plastic, coconut husk, limestone chippings), was pumped down the well, in an attempt to try and mitigate the losses but this had limited success.

This section with intrusions also had further issues when it came to logging runs, with problems running wireline tools. The tools were frequently held up on ledges (208/15-1A End of Well Report) (Fig. 12). In total, the logging and loss of circulation issues resulted in 12 days of NPT.

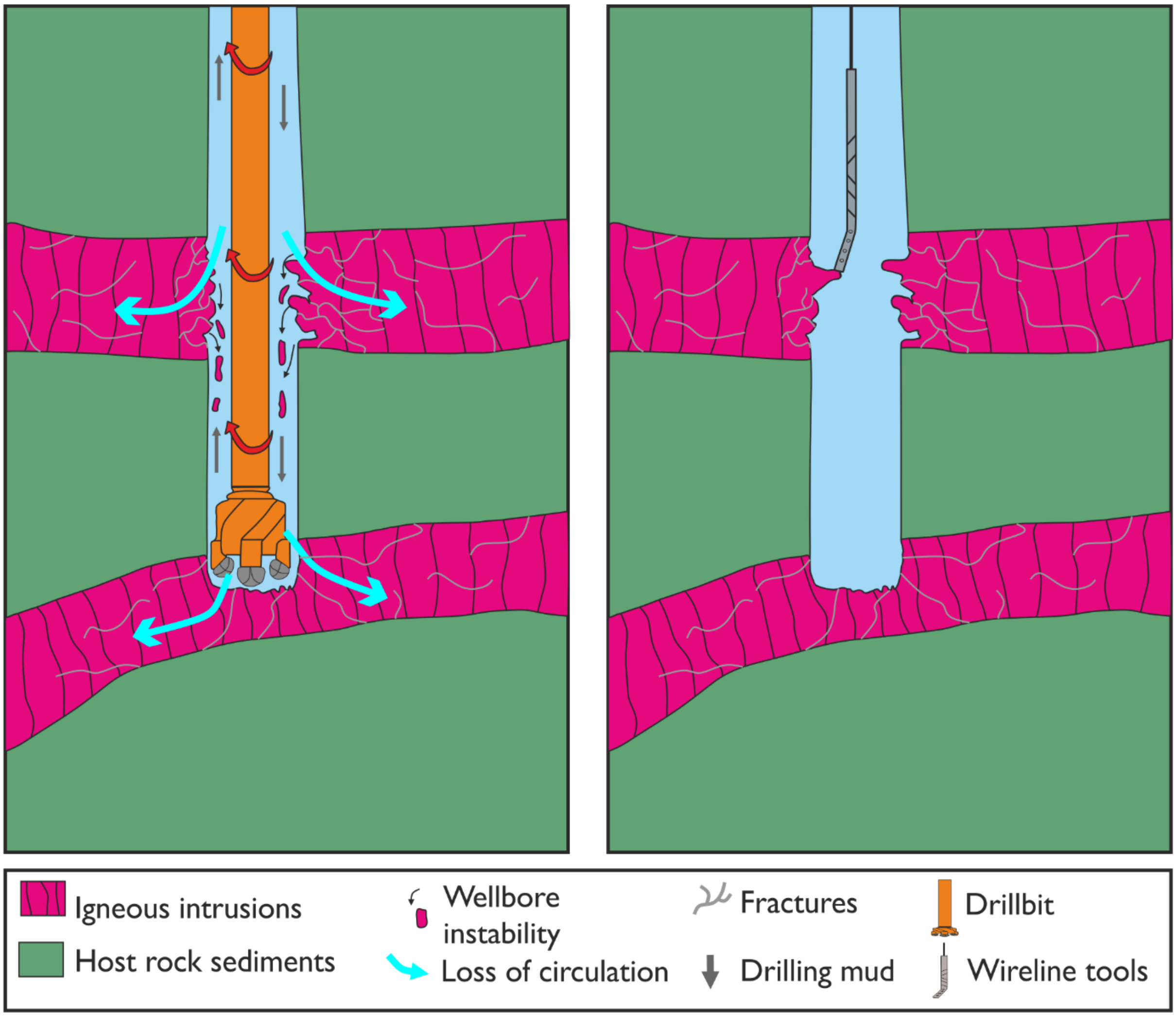
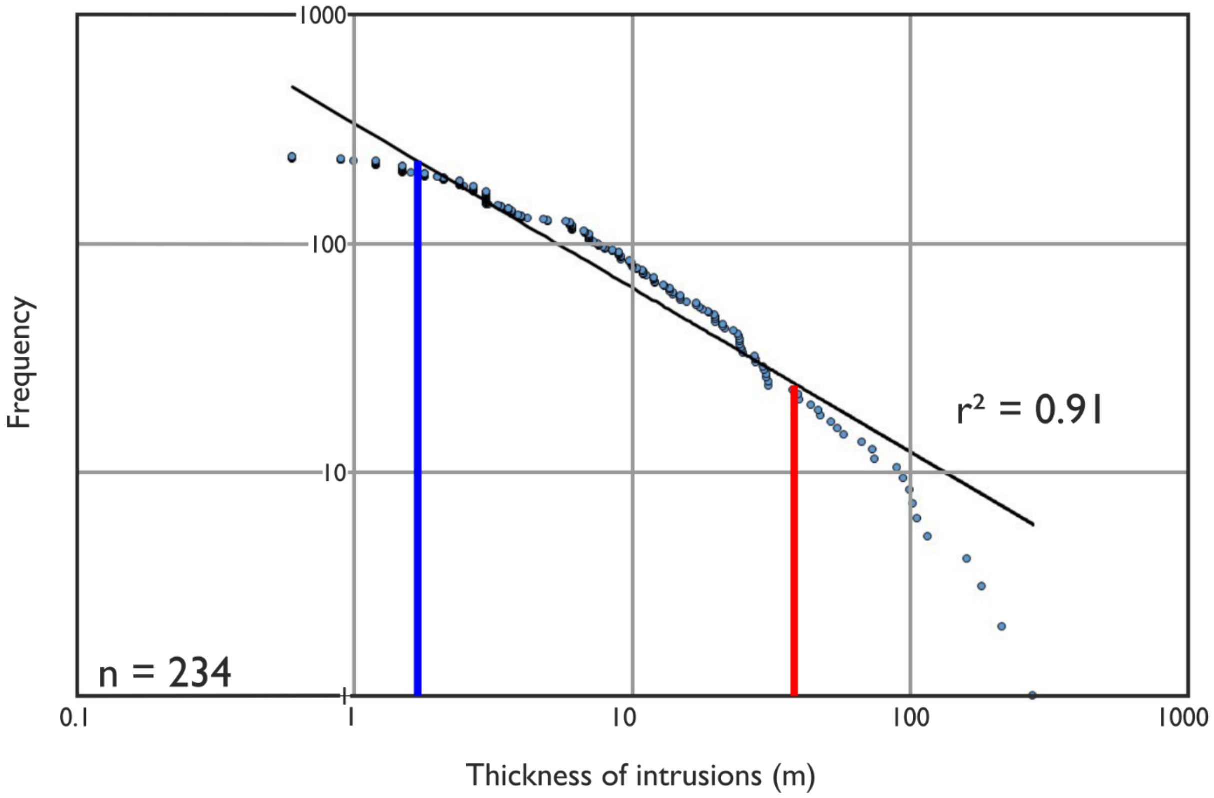


Figure 12: Schematic illustrating the potential impacts intrusions can have on drilling operations including, loss of circulation fluids, wellbore instability and problems running wireline logs.

DISCUSSION

Underestimation of Intrusions on Seismic and Log Data

When the number of intrusions in FSB wells is plotted on a log-log scale, the trend for intrusions encountered below a metre thick deviates from the normal trend line (Fig. 13). However, it is unlikely that this is a true representation of the intrusions in the subsurface but rather a function of the difficulty of resolving sub-metre thick intrusions in wireline or cuttings data. This interpretation is corroborated by core data from 205/10-2B, which retrieved a section of Cretaceous sediments intruded by 15 thin basaltic intrusions ranging in thicknesses from 5-30cm, with a cumulative thickness of 2m (Fig. 14). When the wireline data across this cored interval is examined, no notable variations in the petrophysical response are observed. In the absence of core, it is unlikely that the intrusions would have been noticed (Fig. 14). Observations of intrusions in the field also indicate that there are numerous thin intrusions which propagate off larger intrusions indicating that there is potential for many more intrusions in the FSB than well and seismic data alludes to. This would have important implications for assumptions about melt volumes in the FSB and other magmatically influenced basins worldwide.



FSB Exploration wells:

204/14-1, 204/14-2, 204/16-1, 205/10-2B, 205/10-5A, 206/13-1, 207/01-4Z, 208/15-1A 208/17-1, 208/17-3, 208/19-1 208/21-1, 209/03-1, 209/04-1A, 209/06-1, 209/09-1, 209/12-1, 214/19-1, 214/24-1, 214/27-1, 214/28-1, 219/20-1, 219/28-2Z, 6004, 8a-1, 6004/16-1Z, 6005/15-1, 6104/21-1

Figure 13: Intrusion thickness vs frequency plot for exploration wells in the FSB (plotted on a log-log scale). The blue line indicates the point below which thin intrusions are below the petrophysical resolution; the red line indicates the point above which intrusions are so thick that they are easily identifiable in the subsurface and therefore avoided. The intrusions between the blue and red line represent the majority of intrusion thicknesses in the FSB and are typically below seismic resolution (and therefore would not be recognised pre-drill) but easily resolvable petrophysically once logs have been acquired.

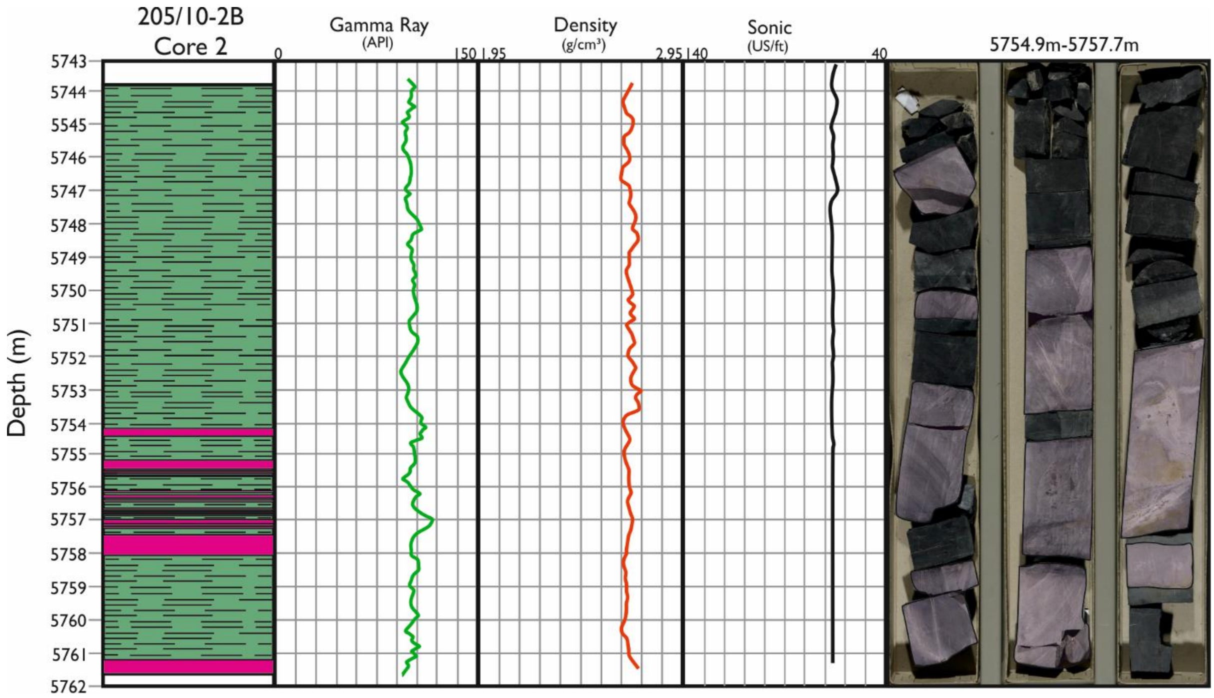


Figure 14: Core from the 205/10-2B well, which contains 10 additional intrusions varying in thickness from 10-30cm compared to the petrophysical response through the section. Note that the intrusions are too thin to be resolved and therefore without the core data, would never have been recognised.

Previous work on intrusions on the Atlantic Margin has focussed on the readily imaged and often visually striking mafic sills (Gibb & Kanaris-Sotiriou, 1988; Bell & Butcher, 2002; Smallwood & Maresh, 2004; Archer *et al.,* 2005; Thomson & Schofield, 2008; Schofield *et al.,* 2012; Schofield *et al.,* 2015). Schofield et al. (2015, 2017) demonstrates that the number (and total thickness) of basaltic intrusions in seismic data along the Atlantic Margin is already likely underestimated. However, as detailed previously, evolved intrusions are particularly difficult to identify within seismic data and even if drilled serendipitously, their discovery would rely on the careful interpretation of petrophysical well logs combined with cuttings and core.

The above observations raise the likelihood that within the FSB and Atlantic Margin, there are considerably more evolved intrusions than previously thought. As the observations from well 205/10-5A indicate, even a 90m thick evolved intrusion is not easily identifiable seismically, on wireline data or indeed during drilling (205/10-5A Geological Report). From the work of Schofield et al. (2015), an intrusion of 90 m thick is statistically less common, with most intrusion thicknesses falling in a 0-40 m range. It may therefore be the case that within FSB wells and the wider Atlantic Margin, evolved intrusions may have been penetrated but gone completely unrecorded in wells and simply classified as sandstones. The only indication that may corroborate the presence of an evolved igneous intrusion would be a drop in ROP. The difficulties identifying igneous intrusions in the subsurface demonstrates the importance of integrating datasets, but as Watson et al. (2017) highlight, the drive to cut costs in future exploration often results in a reluctance to acquire core and run full wireline suites over non prospective intervals, intensifying the issue of misidentification of intrusions within sedimentary basins.

False Exploration Targets – Basaltic Intrusions vs Basement

The 207/01a-4&4Z exploration well targeted high amplitude reflectors which were believed to be sedimentary targets but turned out to be igneous intrusions. Despite the failure of these wells, they yield important lessons about exploration in rifted margins with pervasive igneous intrusions.

The large intrusion encountered in 207/01a-4&4Z is an important consideration for future exploration along the Rona Ridge. Where intrusions have been emplaced along basement highs such as the Rona Ridge, it can be difficult to differentiate high amplitude reflectors which are associated with the top basement and high amplitude reflectors associated with igneous intrusions. In the example of 207/01a-4&4Z, 3D seismic data makes it possible to visualise along strike from the well location where the intrusion crosscuts stratigraphy and has morphologies indicative of an intrusion. The identification is aided by the fact that the intrusion is 213m thick and easily resolvable. However at the top hole location of 207/01a-4, the intrusion appears concordant with the Rona Ridge reflector and is not clearly identifiable as an igneous body. Future exploration along the Rona Ridge and particularly future development of the Southern Clair field, where there are abundant intrusions, may face challenges with differentiating intrusions from the basement horizon.

False Exploration Targets - Basaltic vs Evolved in the FSB

The distinctly different petrophysical and seismic response between basaltic intrusions and evolved intrusions (Fig. 4) was demonstrated in the 205/10-5A and 205/10-2B wells. These evolved intrusions can be misidentified as exploration targets and in order to mitigate this in the future, it is important to understand why the evolved intrusions have such different petrophysical characteristics.

Evolved intrusions differ considerably in petrophysical response to basaltic intrusions due to underlying differences in magma and mineral chemistry (Fig 15). In particular, evolved intrusions have lower densities and sonic velocities compared to their basaltic counterparts. The sonic velocities and densities of the evolved intrusions (e.g. 205/10-5A) are lower as the intrusion mainly consists of minerals with lower elastic properties such as quartz (compressional velocity: 5880m/s, density: 2.65g/cm^3) and orthoclase feldspar (compressional velocity: 4423m/s, density 2.54g/cm^3). The intrusion encountered by well 205/10-5A was also reported as containing numerous amygdales filled with kaolinite (compressional velocity: 6200m/s, density 2.64g/cm^3; Mavko et al., 2009; Rider & Kennedy, 2011). The result of these differences manifests itself in substantial differences in acoustic impedance between mafic and evolved intrusions and as a result, evolved intrusions do not form a typical 'high amplitude' response that is often associated with basaltic intrusions in basins.

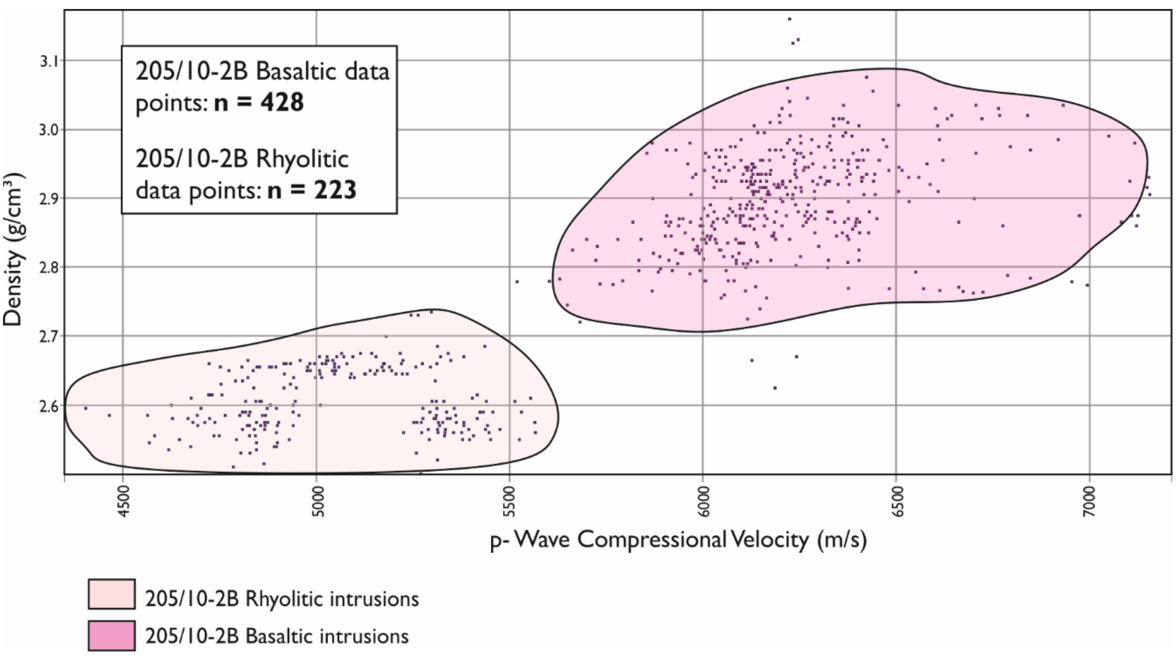


Figure 15: Density vs p-wave crossplot showing the different petrophysical properties of evolved vs basaltic intrusions. The data is for basaltic and evolved intrusions encountered in the 205/10-5A and 205/10-2B wells.

Within well 205/10-5A, which penetrated a 90m thick evolved intrusion, the dominant frequency of the data, even at this relatively deep level in the contemporaneous basin fill, is 22Hz. The average seismic velocity of the Paleocene interval in which the evolved intrusion occurs is 2819ms

(Schofield *et al.,* 2015), leading to a vertical seismic resolution of 32m and a detectability thickness of 16m.

However, despite relatively good vertical resolution of data, the intrusion, which is 90m thick, is difficult to image and is only visible as a weak seismic response with a chaotic seismic character compared to the surrounding seismic data (Fig. 4). This weak seismic response is also corroborated by synthetic modelling (Fig. 16). 205/10-2B, which is only 8km from 205/10-5A, contains a 40m thick intrusion at 3000mBRT which is clearly resolvable.

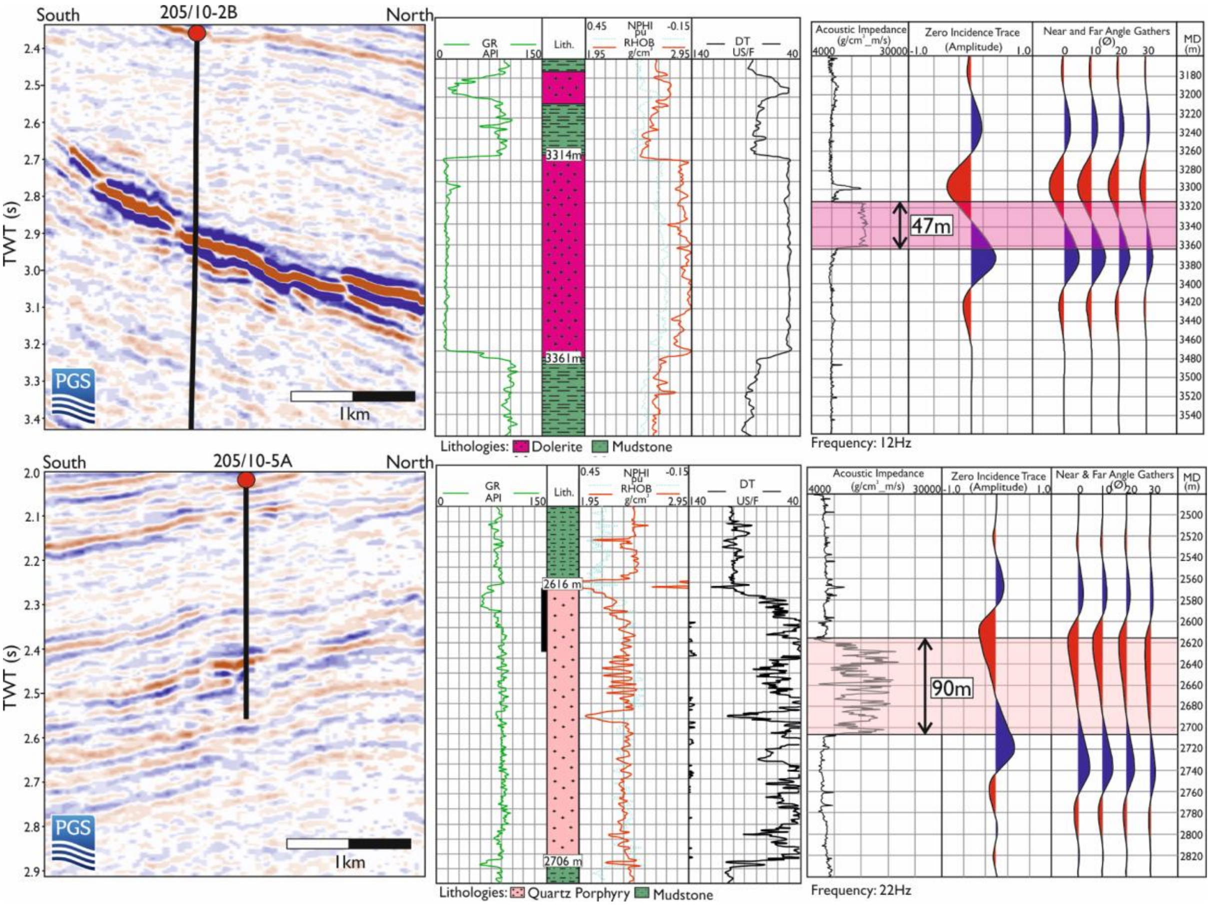


Figure 16: Modelling the synthetic seismic response of the evolved intrusion in 205/10-5A to the basaltic intrusion in 205/10-2B. a) The basaltic intrusion resolves well as it has a high density and sonic velocity resulting in a high acoustic impedance. b) The evolved intrusion does not resolve well due to the lower density and sonic velocities resulting in a lower acoustic impedance. Seismic data courtesy of PGS (PGS FSB MegaSurvey Plus).

Evolved intrusions, particularly those reaching granitic in composition, have much higher viscosities and therefore do not propagate considerable distances from their magma source (Philpotts & Ague, 2009). The fact that they do not flow easily accounts for the observation that the intrusion looks so different to the basaltic intrusions nearby. The seismic morphology is chaotic (Fig. 17) and does not exhibit features like saucer shapes or magma lobes which are common in basaltic intrusions elsewhere in the FSB (Schofield *et al.,* 2015). If evolved intrusions typically do not travel far from the source of the magma, it may indicate that there are more evolved intrusions within that vicinity of the Flett Ridge other than the ones encountered in 205/10-2B and 205/10-5A.

Unfortunately, the substantial difference in seismic imaging between mafic and evolved intrusions led to the drilling of 205/10-5A, which was intended to target a mid- amplitude body that was interpreted to represent turbidite. Furthermore, the chaotic geometry of the intrusion created an amplitude anomaly with a fan-like geometry, making the target appear a likely reservoir (205/10-5A End of Well Report). The well target, which was perceived to be a turbidite fan lobe, turned out to be the 90 m evolved intrusive detailed previously. During drilling, the intrusive body was also cored, as the subsequent quartz-rich cuttings from the intrusion brought up along with the drilling mud was thought to represent the quartz rich sand of the turbidite (Fig. 17)

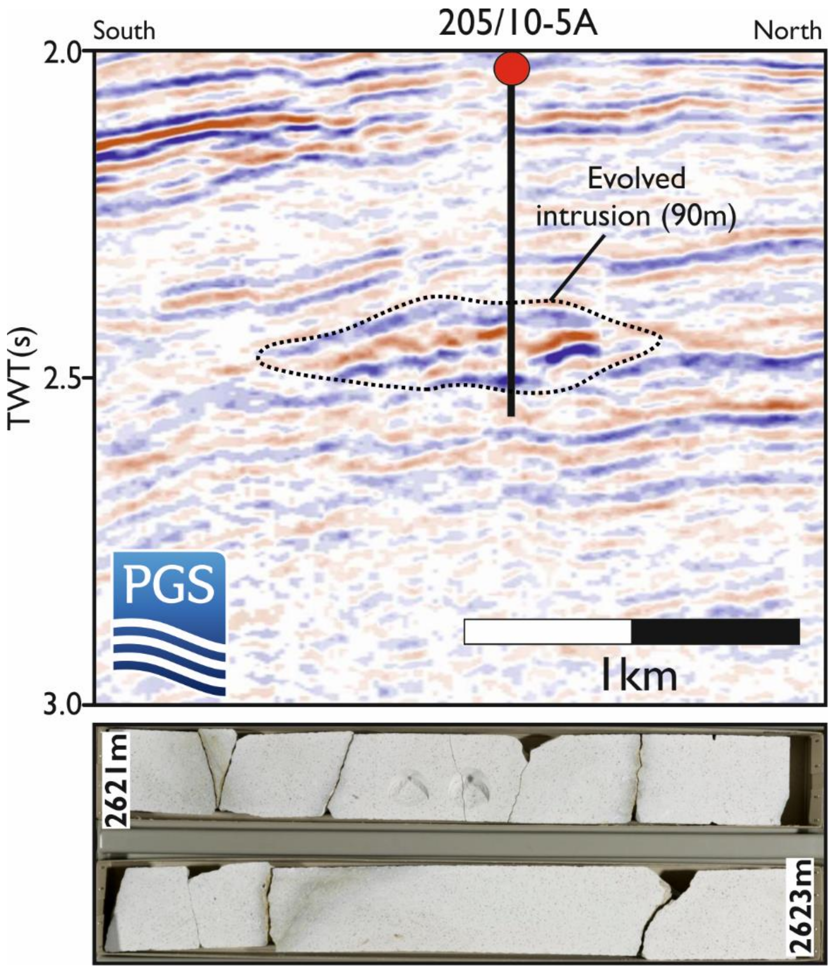


Figure 17: a): Seismic line across the evolved intrusion encountered in the 205/10-5A well. The intrusions is 90m thick but is poorly resolved in seismic data. The pre-drill prognosis was for the amplitude anomaly was a turbidite fan lobe. b): A 2m long cored section of the 90m thick evolved intrusion, core image courtesy of BGS offshore database (BGS 2017). Seismic data courtesy of PGS (PGS FSB MegaSurvey Plus).

In a wider context, the volume of evolved magmatic bodies within the subsurface of the FSB is difficult to estimate. ODP drilling on the VØring Plateau has identified evolved magmas (Eldholm *et al.,* 1989). Evolved extrusives and intrusions have been identified in many of the wells drilled near the Erlend Volcanic Centre (Bell & Jolley, 2002). In the contiguous Rockall Basin to the south-west of the FSB, Morton et al., (1988) commented on the presence of more evolved magmatism identified in the 163/06-1A exploration well. The onshore volcanic rocks of the British Tertiary Igneous Province contain many large evolved igneous centres, such as the Red Hills of Skye and the Arran granite. There are also minor intrusions such as the Drumadoon sill on Arran which is described as a quartz porphyry similar in composition to the intrusion encountered in 205/10-5A. These examples of evolved magmatism identified in other basins are interpreted to be derived from crustal melting of sedimentary rocks by contact with a large body of high-temperature basaltic melt (Morton *et al.,* 1988, Eldholm *et al.,* 1989). The Erlend wells (209/03-1, 209/04-1A and 209/09-1A), which encountered evolved magmatism, were drilled near to the Erlend Volcanic Centre which would have likely been a heat source promoting crustal melting to generate evolved magmatism (Kanaris-Sotiriou *et al.,* 1993).

However, wells 205/10-5A and 205/10-2B were not drilled near any known volcanic centres, although there are numerous large basaltic intrusions imaged on seismic at depth (Fig. 18). These large basaltic intrusions could have caused crustal melting of sedimentary rocks on the Flett Ridge to generate evolved intrusions seen in 205/10-5A and 205/10-2B (BGS Technical Report, The Nature and Origin of Igneous Rocks from Well 205/10-5A). The evolved intrusion in 205/10-5A were interpreted as being peraluminous (BGS Technical Report, The Nature and Origin of Igneous Rocks from Well 205/10-5A) and therefore potentially sourced from melting of clay rich sediments (Morton *et al.,* 1988).

Although from well penetrations these intrusions are relatively rare, the difficulty in even seismically resolving thick evolved intrusions (e.g. 90 m) at shallow stratigraphic levels, brings into question exactly how much evolved magmatism has occurred within the FSB or Atlantic Margin. Future exploration in the FSB and other rift basins should acknowledge the risk of encountering evolved intrusions, in particular the likelihood of them forming false exploration targets.

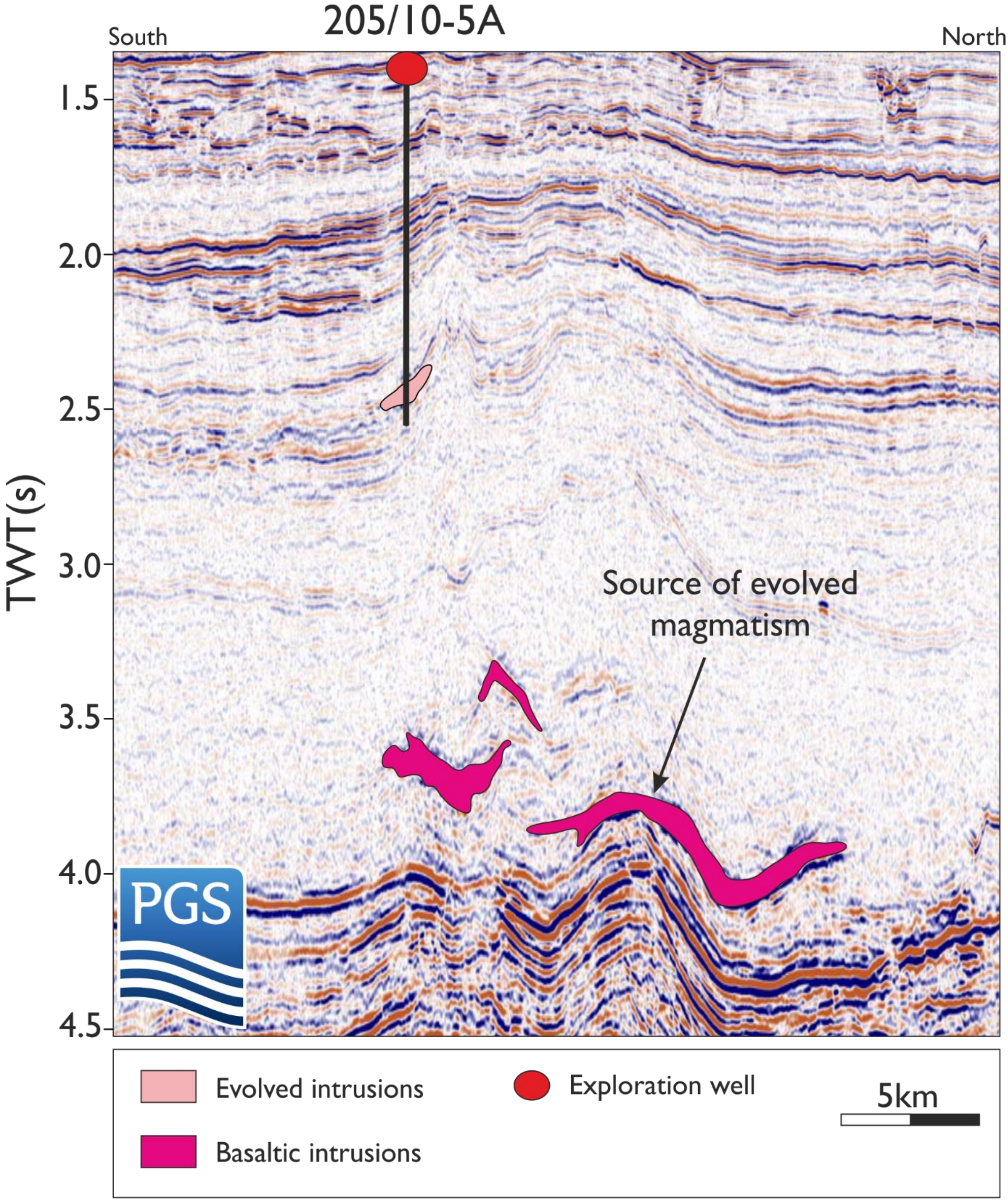


Figure 18: Seismic line showing the large basaltic intrusions at depth which could potentially be the heat source causing crustal melting to generate evolved magmatism. There are no large igneous centres near this location. Seismic data courtesy of PGS (PGS FSB MegaSurvey Plus).

Drilling through Intrusions – Non-Productive Time (NPT) issues

The drilling issues outlined above such as drill bit integrity, slow ROP, undergauge borehole and overpressured intrusions all resulted in additional NPT and in some cases, the premature TD of exploration wells. During hydrocarbon exploration, the biggest cost exposure to a given company is drilling related and therefore, any subsurface scenario that leads to a loss of drilling time, or missing of a target commitment can have significant multi-million pound cost implications.

For the 214/28-1 and 208/15-1A case studies, the total NPT related to intrusions was 34 days. NPT whilst drilling adds additional expenditure to drilling costs and must be minimised. If we assume an average day rate for a drill rig (Semisub >7,500ft: $190,000 (IHS Markit, 2017)) and apply this to the number of NPT days related to issues with intrusions this totals over $6,500,000. This estimate of additional cost is based on lost drilling time and does not include the extra costs associated with damaged bottom hole assembly (BHA) or mud losses. Furthermore, the total NPT detailed above only accounts for a quarter of the wells drilled in the FSB which encountered intrusions, so it is likely that this total number is much higher.

Overpressure and Connection of Deeper Pressure Regimes via Intrusions

Well 214/28-1 and the recent Loanan well are examples of how analysis of the offset well data can inform companies about the potential drilling issues associated with intrusions and how to mitigate these issues in a pre-drill scenario. The Loanan well was prematurely aborted prior to reaching its target depth (total depth TD) due to concerns about encountering overpressured intrusions given the low LOTs (Fig. 10).

The origin of the overpressure associated with the intrusions in 214/28-1 is not fully understood. Within well 214/28-1, the overpressured intrusions encountered are part of a family of intrusions which can be seen to connect down into the deepest parts of the basin, at around 4 km below the sea floor (Fig. 19). Extensive mud losses that have been recorded in many of the igneous intrusions within the FSB indicate that they can have open fractures even at depths of 5000mBRT (Rateau *et al.,* 2013). Therefore, one possible explanation for the overpressure within well 214/28-1 is that the interconnected intrusions acted as fractured conduits, connecting a pressure regime from deeper within the basin (Fig. 19).

Other mechanisms for overpressure generation are related to gas generation (Osborne & Swarbrick, 1997). The abundance of intrusions around the 214/28-1 well location could have caused local thermal maturation of shale host rocks during emplacement generating gas (Svensen *et al.,* 2004), which is a known cause of overpressure (Osborne & Swarbrick, 1997). However, with the repeated instances of loss of circulation events within intrusions in the FSB, implying an open fracture system, the risk that intrusions could act as conduits vertically though the basin connecting different pressure regimes needs to considered.

In the case of the Loanan well, the planned TD for the well was <200m above the nearest, seismically imaged-intrusion (Fig. 9). Recent field work focused on sills in outcrop emphasises that it is common to see multiple thin splays or offshoot intrusions propagating away from large intrusions (Fig. 9); this effect is particularly pronounced in siliciclastic dominated intervals, which typically form hydrocarbon reservoirs (Eide *et al.,* 2017). As the Loanan well approached the secondary reservoir target, the potential for encountering multiple thin splays off the large intrusion would be increased (Fig. 9). Inspection of the current seismic data appears to show thin reflectors intruding the base of the secondary target, possibly indicating an increased risk of communication between the reservoir and intrusion (Fig. 9).

For future exploration in the FSB, and particularly the Flett Sub-basin around well 214/28-1, a different approach with respect to drilling design is needed in order to deal with issues related to overpressured sills and the eventuality of weaker than expected stratigraphic formations (which will affect the maximum mud weight that can be used).

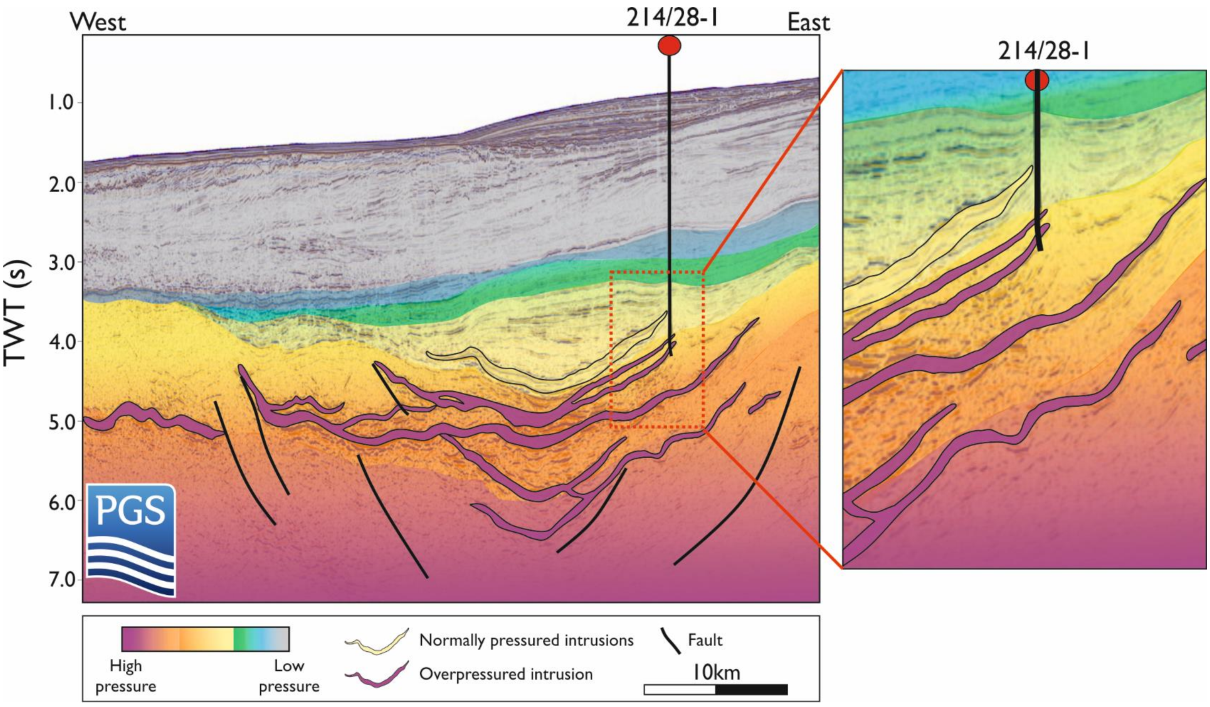


Figure 19: Seismic line through the 214/28-1 well, which shows the intrusions plumbing into the deepest parts of the basin. The Seismic line is schematically coloured to infer different pressure regimes and how the interconnected intrusions could result in shallow intrusion having pressures similar to pressures encountered in the deepest part of the basin. This could potentially explain the overpressured intrusions encountered in 214/28-1. Seismic data courtesy of PGS (PGS FSB MegaSurvey Plus).

Rigid Frameworks Resulting in Disequilibrium Compaction

In well 209/04-1A, overpressure was observed during a sudden lithology change from a 270 m thick rhyolitic intrusion to Upper Cretaceous claystones at 3085mBR. It is possible that the impermeable intrusion prevented normal compaction and lead to disequilibrium compaction whereby pore fluids within the claystones were unable to escape. This results in the pore fluid pressure rising above hydrostatic (Osborne & Swarbrick, 1997). It was below this intrusion that the overpressure was encountered, resulting in the need to raise the mud weight to 10.8ppg, resulting in mud losses. Prior to drilling into the claystone, a fracture integrity test was carried out in the intrusion giving a result of 13.4ppg EMW, indicating that a mud weight of 10.8ppg would not fracture the formation. This misalignment between expected fracture integrity and the mud weight, which resulted in fracture of the formation, is caused by the fracture integrity test being carried out in the intrusion, which has much stronger mechanical strength compared to the claystone below (Fig. 11).

CONCLUSIONS

This work demonstrates the different seismic and petrophysical characteristics of igneous intrusions in the FSB and by using case studies from explorations wells, demonstrates their impact on hydrocarbon exploration. Exploration is ongoing in the FSB and due to the areal extent of the Faroe-Shetland Sill Complex and its proximity to oil and gas fields, it is important that the intrusions are studied and their implications for the petroleum system understood. The findings can be summarised as;

- Thin intrusions are difficult to identify in the subsurface due to seismic and logging tool limitations. The difficulty identifying intrusions in the subsurface means that it is likely that many more intrusions are present in basins. Combined with the difficulties associated with identifying evolved intrusions, estimates of melt volumes in rift basins are likely to be underestimated.
- The FSSC has previously been identified as mainly comprising basaltic intrusions but this study presents examples of evolved magmatic bodies.
- In contrast to basaltic magma, the distinct petrophysical and seismic properties of the evolved intrusions make them difficult to identify in the subsurface and as a result, can be misidentified as exploration targets.
- Where intrusions have been encountered in the subsurface, this has commonly resulted in issues such as low ROP, drill bit integrity, loss of circulation, cavings and overpressure.
- The 214/28-1 and Loanan case study reveals the difficulties associated with targeting prospects close to intrusions, such as drilling issues or premature TD as a result of a low LOT and risk of encountering overpressured intrusions.

In summary this study shows that intrusions can have significant implications for hydrocarbon exploration. The igneous intrusive complex in the FSB extends into the contiguous Møre Basin to the north, and the Rockall Basin to the south so utilising the knowledge gained from the FSB would be beneficial for future exploration in these regions and other volcanic margins globally.

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SUPPLEMENTARY MATERIAL

Drilling Acronym/Terminology	**Definition**
ROP (rate of penetration)	The speed at which the drill bit can break the rock to deepen the well bore.
WOB (weight on bit)	The amount of downward force exerted on the drill bit.
Drilling mud/ Equivalent Mud Weight	Drilling mud maintains the hydrostatic pressure within the wellbore and also transports drill cuttings to the surface.

BHA (bottom hole assembly)	Lowest part of the drill string. This contains the drill bit, drill collar, measurement-while-drilling tools (not always run).
Drill bit	The tool used to cut the rock.
Drillstring	Combination of drillpipe, the bottom hole assembly.
NPT (non-productive time)	Time which is not spent drilling the hole.
RPM (revolutions per minute)	How quickly the drillstring rotates.
Casing	Casing is carried out every time the well drills to a new a certain depth and the wellbore diameter is changed. Casing prevents the formation caving into the wellbore and also controls formation fluids and pressures.
FIT (Fracture integrity test or formation integrity test)	Test of the strength and integrity of a new formation. Commonly occurs after a casing point to determine the suitable mud weight to contain the well.
LOT (Leak off test)	Similar to a FIT but this tests the formation to the point that it fractures. This allows the determination of the maximum mud weight which could be sustained before fracturing the formation. LOT measures the strength of the formation and informs what mud weight can be used before the formation will fracture and incur mud losses.
Overpressure	Subsurface pressure which is abnormally high and exceeds hydrostatic.

Underbalanced drilling	The pressure in the wellbore is lower than the pressure of the formation being drilled, resulting in fluids flowing into the wellbore. Left unchecked, this can result in a potential blowout.
Overbalanced drilling	The pressure in the wellbore is higher than the formation pressure to prevent fluids flowing into the wellbore. If too high, this can lead to fracturing and damage of the formation being drilled through.
Loss of circulation	Drilling mud is lost into the formation either through an open fracture network in the subsurface, or induced fractures due to the mud weight being too high.
Underguage	Undergauge hole occurs in abrasive formations when the well bit becomes worn, resulting in a smaller wellbore diameter. See 'Reaming' below.
Ledges	Ledges are coherent blocks/bodies which remain stable forming tight spots which are obstacles for wireline tools (Millet *et al.,* 2016) corresponding to the intrusions.
TD (total depth)	The total depth that the well drills.
Reaming	Enlarging the wellbore to maintain wellbore diameter.
Twist off	Separation or breaking of the drillstring downhole. Can be caused by excessive torque.

Cavings/well bore instability	Pieces of rock that fall into the wellbore but are not a result of drilling action.